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MACHINING PERFORMANCE AND CARBON FOOTPRINT ANALYSIS OF INCONEL 718 USING DIFFERENT MINIMUM QUANTITY LUBRICATION OILS

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
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IN
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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

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I certify that this thesis satisfies all the requirements as a thesis for the degree of **Master of Science in Mechanical Engineering, Atılım University**.

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ABSTRACT

MACHINING PERFORMANCE AND CARBON FOOTPRINT ANALYSIS OF INCONEL 718 USING DIFFERENT MINIMUM QUANTITY LUBRICATION OILS

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Inconel 718 is highly suitable for high-temperature applications due to its exceptional corrosion and oxidation resistance, along with its high strength at elevated temperatures. However, its high hardness, wear resistance, and significant work hardening rate make its machining challenging. Conventional Cutting Fluids (CCFs) are inadequate for addressing these challenges and are not sustainable due to their high consumption and harmful effects on human health and the environment. Minimum Quantity Lubrication (MQL) has emerged as an effective alternative to CCFs. By delivering a small amount of oil mixed with compressed air in aerosol form to the cutting zone, MQL promotes sustainable and environmentally friendly manufacturing, particularly for hard-to-machine materials like Inconel 718. The aerosol delivery method improves penetration between the cutting tool and workpiece, enhancing efficiency. However, the oils used in MQL applications directly affect machining performance, making it crucial to develop oils specific to the material being machined. In this study, three different MQL developed to improve the machining performance of Inconel 718 were first tested for their physical characteristics and performance. Subsequently, their performance during slot milling experiments of Inconel 718 material was evaluated. A comparative investigation of CCFs, dry machining and MQL is provided with the focus on critical performance metrics including cutting forces, tool wear, surface finish alongside an assessment of environmental impact and sustainability in terms of carbon footprint. The findings demonstrate that MQL significantly enhances machining performance while reducing carbon emissions, offering a more viable solution for efficient and sustainable machining of Inconel 718.

Keywords: Minimum Quantity Lubrication, Sustainability, Carbon Emissions, Inconel 718

ÖZ

INCONEL 718'İN FARKLI MİNİMUM MİKTARDA YAĞLAMA YAĞLARI KULLANILARAK İŞLEME PERFORMANSI VE KARBON AYAK İZİ ANALİZİ

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Inconel 718, üstün korozyon ve oksidasyon direnci ile yüksek dayanım özellikleri sayesinde yüksek sıcaklık uygulamaları için son derece uygun bir malzemedir. Ancak, yüksek sertliği, aşınma direnci ve belirgin işleme sertleşme oranı nedeniyle işlenmesi zordur. Geleneksel Kesme Sıvıları (GKS), bu zorlukların üstesinden gelmede yetersiz kalmakta ve yüksek tüketim oranları ile insan sağlığına ve çevreye olan zararlı etkileri nedeniyle sürdürülebilir bir çözüm sunmamaktadır. Bu nedenle, Minimum Miktarda Yağlama (MMY), GKS'ye etkili bir alternatif olarak dikkat çekmektedir. Sıkıştırılmış hava ile karıştırılan az miktarda yağın aerosol formunda kesme bölgesine iletilmesiyle, MMY özellikle Inconel 718 gibi işlenmesi zor malzemeler için çevre dostu ve sürdürülebilir bir üretim yöntemi sunmaktadır. Aerosol uygulama yöntemi, kesici takım ile iş parçası arasındaki bölgeye daha iyi nüfuz ederek işleme verimliliğini artırmaktadır. Ancak, MMY uygulamalarında kullanılan yağların doğrudan işleme performansını etkilemesi, işlenecek malzemeye özgü yağların geliştirilmesini kritik hâle getirmektedir. Bu çalışmada, Inconel 718'in işlenebilirliğini artırmaya yönelik olarak geliştirilen üç farklı MQL yağı önce fiziksel özellikleri ve performansları açısından test edilmiştir. Ardından, Inconel 718 malzemesi üzerinde yapılan kanal frezeleme deneylerinde performansları değerlendirilmiştir. Geleneksel İşleme (Gİ), kuru işleme ve MMY yöntemleri karşılaştırmalı olarak ele alınmış; kesme kuvvetleri, takım aşınması, yüzey kalitesi gibi temel performans metriklerine ek olarak, çevresel etki ve sürdürülebilirlik, karbon ayak izi temel alınarak değerlendirilmiştir. Elde edilen bulgular, MMY yönteminin işleme performansını önemli düzeyde artırırken karbon salımını azalttığını ve Inconel 718'in verimli ve sürdürülebilir şekilde işlenmesi için daha uygun bir çözüm sunduğunu ortaya koymaktadır.

Anahtar Kelimeler: Minimum Miktar Yağlama, Sürdürülebilirlik, Karbon Emisyonları, Inconel 718

To my loving family

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LIST OF SYMBOLS/ABBREVIATIONS

ANSI	American National Standards Institute
BF	Base Fluid
CA	Cooling Agent
CC	Amount of Cutting Fluid
CCF	Conventional Cutting Fluid
$CE_{c/l}$	Carbon emissions related to the used coolant-lubricant
CE_{chip}	Carbon emissions associated with chip recycling
$CE_{electric}$	Carbon emission related to electricity consumption
$CE_{material}$	Carbon emission related to production of raw material
CE_{oil}	Carbon emission related to production of mineral oil
CE_{tool}	Carbon emission related to production of the cutting tool
CE_{total}	Total carbon emissions related to complete machining operation
$CE_{wc/l}$	Carbon emissions from disposal of cutting fluid
CEF	Carbon emission factor
CEF_{chip}	Carbon emission factor of chip recycling
$CEF_{electric}$	Carbon emission factor of electricity
$CEF_{material}$	Carbon emission factor of raw material
CEF_{oil}	Carbon emission factor of cutting fluid production
CEF_{tool}	Carbon emission factor of the cutting tool
CEF_{wc}	Carbon emission factor of waste disposal of cutting fluid
CM	Conventional Machining
CMQL	Cryogenic Minimum Quantity Lubrication
CO_2e	Carbon Dioxide-Equivalent
cSt	Centistoke
CVD	Chemical Vapor Deposition
D	Depth of Cut
DE	Diester
δ	Predetermined cutting fluid concentration

E_{cut}	Energy spent during the actual cutting
EC_{oil}	Carbon Intensity of Mineral Oil
EC_{total}	Total energy consumption of the CNC machining operation
EE_{oil}	Emobodied Energy of Mineral Oil
EM	Emulgator
EMQL	Electrostatic Minimum Quantity Lubrication
F	Feed Rate
FFT	Fast Fourier Transform
F_r	Resultant Cutting Force
GHG	Greenhouse Gas
GWP	Global Warming Potential
HNMQL	Hybrid Nanofluid Minimum Quantity Lubrication
HOVO	Highly Oleic Vegetable Oil
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardization Organization
M_{chip}	Mass of the chip removed
MD	Metal Deactivator
MQL	Minimum Quantity Lubrication
MRR	Material Removal Rate
MWF	Metal Working Fluid
NMQL	Nanofluid Minimum Quantity Lubrication
P_{cut}	Cutting Power
PAG	Polyalkylene Glycols
PAO	Polyalphaolefin
PE	Polyol Ester
PVD	Physical Vapor Deposition
TAN	Total Acidic Number
t_{cut}	Cutting time
TMPTO	Trimethylolpropane Trioleate
T_{tool}	Tool life
Sa	Areal Average Roughness
V_{cut}	Cutting speed

VB	Flank Wear
VI	Viscosity Index
W	Width of Cut
Q	Flow Rate
W_{tool}	Mass of the cutting tool

CHAPTER 1

INTRODUCTION

The curiosity in human nature and the endless strive for improvement results with development in science, technology and therefore society. Multiple factors such as the market competition, increasing technological capabilities and performance improvements lead to a demand in creating new products with improved properties. To fulfil these requirements, materials that can be used in multiple sectors with unique mechanical, chemical, thermal and electrical characteristics including composites and super alloys are introduced to the engineering scenery. From the standpoint of aerospace industry, components such as turbine engines, rocket motors, and components of spacecraft are required to maintain their mechanical integrities and be able to withstand extreme operating conditions. This requires a selection of durable materials with high strength properties and the ability to maintain these features at elevated temperatures. Nickel is a metal that is known for its hard, ductile and corrosion resistant properties and its ability to preserve these features even at high temperatures due to its high melting point [1]. Therefore, it is widely used in the steel-alloy production industry and the resultant materials are highly demanded for aerospace industry related components. Among the nickel-based alloys, Inconel 718 is a prominent material. It is one of the most popular nickel-based superalloys, known for its exceptional strength and resistance to corrosion and oxidation, even at temperatures up to 650 ◦C [2] [3].

Machining is a widely adopted method for the manufacturing of aerospace components from raw materials. In machining, the desired shape, size and surface quality are obtained through the elimination of extra material in the form of tiny chips, making it arguably one of the most flexible manufacturing techniques. This process requires direct contact between cutting tools and workpiece material. As a result of this relative motion, friction occurs and it causes a generation of increased temperature between the cutting tool and workpiece material contact area [4]. When high strength materials such as Inconel 718 are machined, as the temperature rises, cutting tool's strength decreases; resulting in more tool wear and decrease of the tool life [5]. In order to maintain a controlled temperature, the cutting zone between the tool and the work piece must be continuously cooled down. The cutting tool's sharpness could be affected by overheating. When a blunt tool is used, it results with a higher power consumption and leaves a rough surface finish on the part [6].

Machinability of a material is often influenced by its properties and refers to how easy or hard it is for a material to be machined and formed into the desired geometry. It is also influenced by the factors including the cutting environment and cutting tool rigidity [7]. Inconel 718 is infamously known for being hard to machine because of its high strength, thermal resistivity and work hardenability characteristics thus, resulting wear on the cutting tool and lowering its tool life [2][8]. Even though Inconel 718 itself can withstand high elevated temperatures, it has rather low thermal conductivity, resulting the heat generated during machining not dissipate quickly and therefore overheating the cutting tool contact area [9]. Inconel 718 also shows a tendency to work harden during machining, which is the phenomenon of increasing hardness of a material as it goes under mechanical operations and gets deformed [10][11]. The resultant heat generation negatively affects the tool life and when the tool has reached its end-of-life, it requires a replacement [12]. Also, poor surface finish as the result of heat may lead to further operations for improvement. The aftermath of such cases would be unwanted time and financial consumptions.

To minimize such problems Metal Working Fluids (MWF) are used both as a lubricant and a coolant in machining process. The types of MWF include aerosols (mists) gels, pastes, oil, oil-water emulsions, air and other gases. In most cases, the water-oil emulsions MWF are preferred in the machining industries. Even though usage of such fluids benefits the overall machining process, its application also causes some environmental and occupational health problems because of the microbial growth from MWF emulsions of oil and water [13] [14].

In order to advance sustainable development and lessen the threat to our health and environment and to limit the amount of cutting fluid usage, two alternative approaches are introduced by researchers: First one is the development of new cutting fluids by altering the composition of the cutting fluid, improving the lubrication and cooling effects of the cutting fluid. This can decrease the amount of cutting fluid used. The second one is retrofitting the lubricating and cooling technologies [15].

With the need of reduced cutting fluid used methods, various techniques of machining including dry machining, cryogenic machining and Minimum Quantity Lubrication (MQL) are introduced to sustainability area. In recent years, the increase of environmental awareness led to more research and exploration regarding these techniques. Among these alternatives, the sustainability features including ability to use biodegradable oils, minimal consumption and high-performance efficiency increased the importance of MQL [16]. Additionally, when compared to Conventional Cutting Fluids (CCFs), MQL has resulted more sustainable in terms of costs with its fluid usage being minimum and in ecological aspects, MQL has become much preferable since it doesn't require disposal and is mostly safe with utilization of environmentally safe oil-based fluids, making it a very important cooling method of machining [17].

Sustainability in machining can be defined as the application of practices and processes that minimize environmental impact while promoting economic, social and environmental responsibility[18]. To achieve this, manufacturers should focus on resource and energy efficiency as well as waste management and reducing greenhouse gas emissions. By considering the energy spend as the result of cutting forces and the amount of cutting fluid used and its disposal, it is possible to make a machining operation more sustainable. The energy consumed during machining operations is directly related to the amount of applied force from cutting tool to the workpiece [19]. Therefore, the cutting tools are generally selected by considering them having better mechanical properties than the workpiece materials [20]. MQL stands out in terms of less fluid usage and disposal. The ability to use vegetable-based oils in MQL also makes it a sustainable option among its alternatives since in general, the production of vegetable-based oils results fewer emissions when compared to the industrial ones [21].

Greenhouse emissions refer to the release of a group of gases as a result of any human activity. The release of GHGs cause a formation of trapped heat in the earth's atmosphere and therefore global warming. GHGs mainly include, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases which includes hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) [22]. The carbon footprint is measured in terms of carbon dioxide equivalents (CO_2e), calculated by multiplying the quantity of each greenhouse gas emitted by its Global Warming Potential (GWP). GWP represents how effectively a specific greenhouse gas traps heat in the atmosphere compared to carbon dioxide, which is used as the baseline reference. [23]. A more detailed explanation is given in Chapter 3.

The calculation of carbon emissions related to a machining operation or any activity can be categorized as direct and indirect emissions. When machining is considered, the components that contribute to the operation directly are usage of the workpiece material, machine tool (e.g. CNC machining centers), energy, cutting tool and cutting fluid. The consumption or production of each of these components results with the release of GHGs [19].

The main purpose of using MQL system is to minimize the problem of inadequate cooling and lubrication when applying milling operation to the Inconel 718 material. In this experimental study, it is aimed to observe the effects of MQL which in our case, adapts various polyol and polymeric ester-based oils with diverse chemical structures on slot milling of Inconel 718 then investigate the results by making a comparison with the results of more CCF and dry machining alternatives. By enhancing the cooling and lubrication abilities, it is expected to observe improvements in surface quality and cutting force values [6]. Furthermore, since the fluid usage is minimal in MQL, the total carbon emission values of it is also expected to show better results than its alternatives.

1.1 Thesis outline

The first chapter of the thesis provides a comprehensive overview of the overall structural framework and organization of the thesis.

In the second chapter, detailed definitions of the components and concepts associated with the thesis are given and efficiency, sustainability and performance improvements in machining with the application of MQL in comparison to dry and flood machining is evaluated with respect to literature. Additionally, calculation methods of GHG emissions in machining operations are provided.

In the third chapter of the thesis, the explanation of the machining conditions using MQL, dry and CCF methods are given. The details of the experimental setup including the machine tool, cutting tool, workpiece material, adapted cutting fluids and measurement devices are given. The measurement methods of cutting forces, surface roughness, surface topography and CO_2e emissions are provided.

Lastly, in chapters 4 and 5, the attained results are interpreted and summarized and future study recommendations based on these findings are provided.

CHAPTER 2

LITERATURE REVIEW

2.1 Inconel 718

2.1.1 Introduction

Nickel is a silvery-white lustrous metal, designated by the chemical symbol Ni and holds the atomic number 28. It has a melting point of 1454 °C, which is marginally lower than that of iron at 1535 °C. Exhibiting both hardness and ductility, nickel crystallizes in a face-centered cubic (FCC) structure that remains stable up to its melting point without undergoing phase transformations [24]. The metallurgy associated with nickel alloys is notably complex. Pure nickel is often combined with elements such as copper, iron, chromium, titanium, tungsten, molybdenum, niobium and aluminum to form alloys. Among them, solid solution strengthened variations, especially the ones that incorporate chromium and copper, display outstanding corrosion resistance in environments containing seawater, hydrofluoric acid, sulfuric acid, and various alkaline substances. These elements are strategically added to form alloys enhance high-temperature strength through three primary strengthening mechanisms [25]:

- Solid solution strengthening (W, Cr)
- Precipitation strengthening via the formation of stable intermetallic compounds (Ti, Al, Nb)
- Oxidation resistance at high temperatures and precipitation strengthening (Ta)

The aerospace industry is responsible for 70% of the total consumption of the superalloys shown in Figure 2.1 [26]. Nickel based alloys are widely recognized in the aerospace industry by composing nearly half of the total material required in the manufacture of an aircraft engine because of their excellent strength even at elevated temperatures [27].

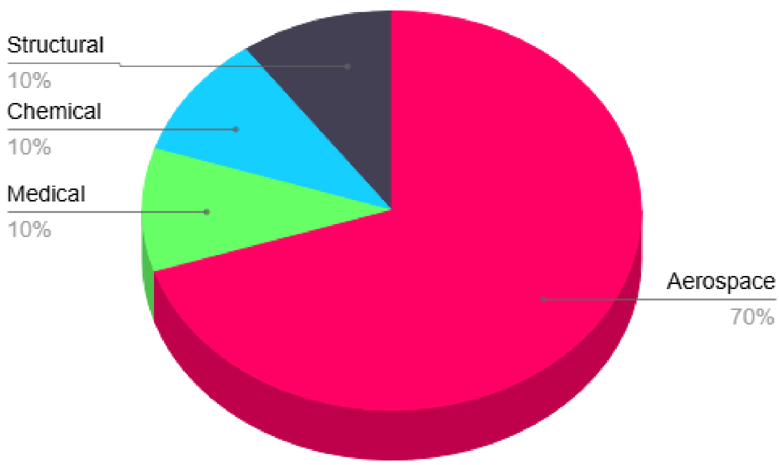


Figure 2.1 Consumption of superalloys by different sectors [26]

However, Nickel based alloys are also infamous for their challenging machinability due to their characteristics and their other inherent properties including exceptional hardness, a pronounced tendency to chemically interact with cutting tools, and notably low thermal conductivity. During machining, the peak temperatures are concentrated at the tool's cutting edge and this localized heating leads to significant thermal stress at the cutting tool tip, increasing the risk of tool deformation and premature failure. The absence of a cooler zone near the cutting edge exacerbates this issue, contributing to the classification of nickel and its alloys as materials that are particularly difficult to cut.

The term "Inconel" describes a series of austenitic superalloys based mainly on nickel and chromium. These alloys are known for their excellent resistance to corrosion and oxidation, making them highly suitable for extreme environments involving high heat and pressure. Among them, Inconel 718 is a precipitation-hardened nickel–chromium alloy that is notoriously difficult to machine, primarily due to its high yield strength and hardened structure. It was originally engineered for aerospace and gas turbine applications and composing up to 50% of a jet engine's total weight [28] as shown in Figure 2.2 [29].

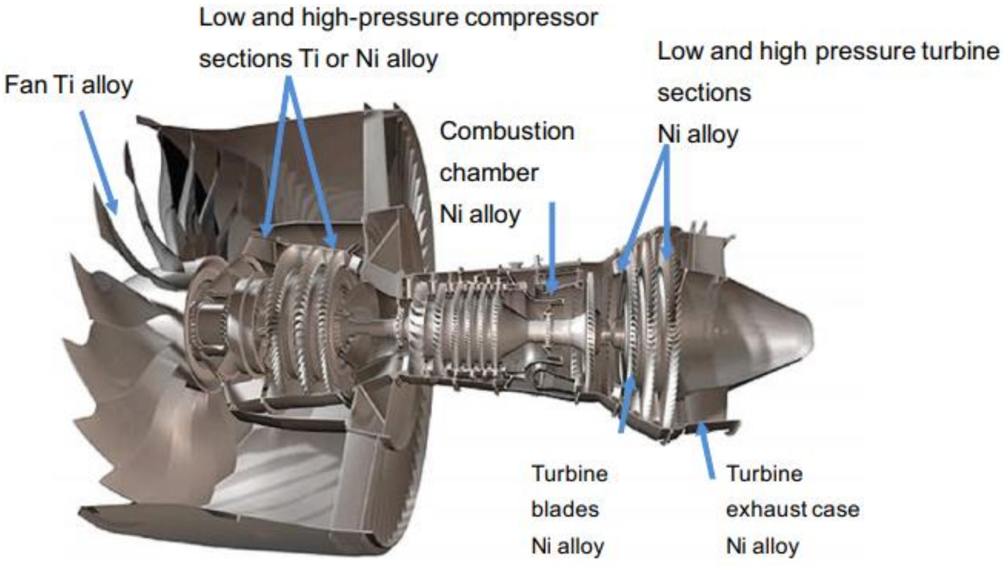


Figure 2.2 Usage of Nickel based superalloys in jet engines [29]

Inconel 718 has also become a preferred material in the oil and gas sector. Its exceptional mechanical strength and corrosion resistance under extreme conditions have led to its widespread adoption in manufacturing wellhead components, downhole tools, and subsurface safety valves [30]. Key properties of Inconel 718 include:

- Strong resistance to chloride and sulfide induced stress corrosion cracking
- Superior mechanical strength after aging treatment
- Excellent overall corrosion resistance

2.1.2 Machining of Inconel 718

Dudzinski et al. [31] listed the physical properties that determines Inconel 718 as difficult to cut as:

- High material strength at increased temperatures,
- Low thermal conductivity,
- Work hardening,
- Chemical affinity to most of the tooling materials,
- Contamination of hard carbide particles,
- High machining forces and vibrations,

- Tendency to adhesion and welding which causes Built-Up Edge (BUE) formation.

Inconel 718 tends to work-harden significantly after the first cutting pass, which can lead to deformation of either the tool or the workpiece during following cuts. As a result, when machining Inconel 718, it is important to apply a slow, aggressive cutting strategy using hard tooling to minimize the number of passes. Typically, low cutting speeds are employed to limit tool wear even though this reduces productivity. High cutting speeds lead to increased temperatures in the cutting zone which can leave burn marks [32]. Additionally, because Inconel 718 retains high strength at elevated temperatures, significant cutting forces persist at high machining speeds due to the intense heat generated during the process. A feed rate that is too slow can cause the tool to continuously cut through the hardened layer formed in prior passes, accelerating tool degradation. On the other hand, an excessively high feed rate can generate cutting forces large enough to cause catastrophic tool failure [24].

Cutting tool selection is another factor that affects the resulting surface quality. While selecting the tool, mainly, the deciding parameters must be its wear resistance, hardness, fracture toughness and chemical affinity to the workpiece material. Depending on the material type and coatings, different forms of wear occurrence are observed in the cutting tools [33]:

- Abrasion and adhesion in coated carbide,
- Abrasion in uncoated carbide,
- Adhesion and diffusion in Cubic Boron Nitride,
- Abrasion, diffusion and plastic deformation in Ceramic.

Temperature of the cutting zone is a crucial factor that affects the cutting force, tool life and surface quality. During the machining processes, the workpiece material undergoes significant plastic deformation due to tool engagement. Most of the energy used in this process converts to heat, causing the temperature near the tool tip to rise until a steady state is reached. The main source of this heat is plastic deformation in the shear zone.

Additional heat is generated through friction at two contact areas: between the chip and the tool's rake face (secondary deformation zone), and between the tool's flank face and the newly cut surface (tertiary deformation zone). These friction zones, under high pressure, contribute to further thermal buildup. In the primary zone, heat results from elastic and plastic deformation; in the secondary zone, from chip-tool friction and some plastic flow; and in the tertiary zone, mainly from friction and elastic rubbing on the finished surface. The deformation zones are shown in Figure 2.3 [34].

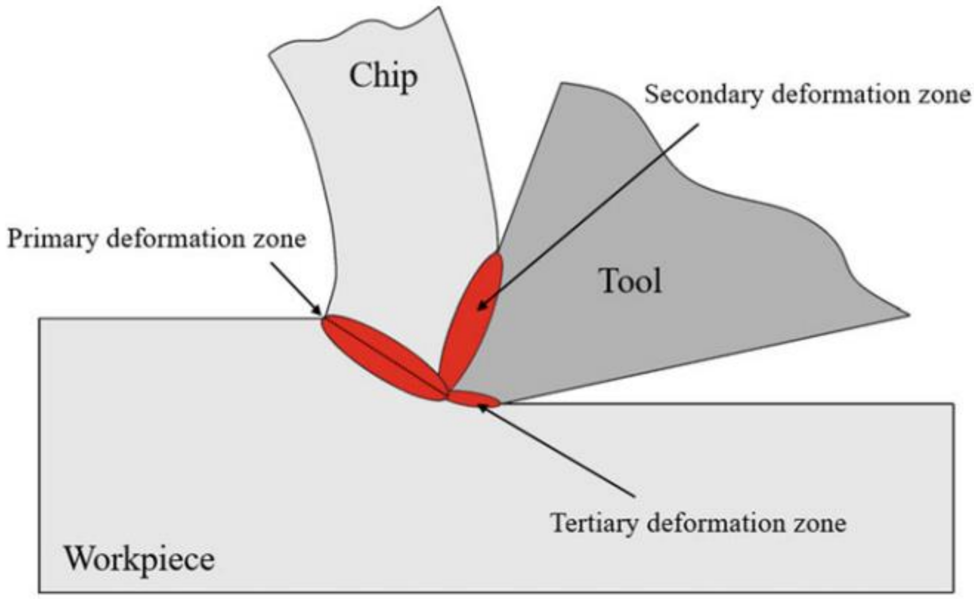


Figure 2.3 Deformation zones in machining [34]

For difficult cases of elevated temperatures in operations such as the utilization of Inconel 718, optimization of the machining parameters will not be enough to obtain satisfactory results and additional agents or cutting fluids are required for cooling.

2.2 Cutting Fluids in Machining

The usage of fluids specifically designed for metal cutting operations began in the early 1900s [35]. Initially, water was the only alternative for cooling the workpiece - cutting tool contact area [36]. Cutting fluids that contain water soluble oils started to develop later with the aim of adding lubrication features to metal cutting and in today's metal cutting industry, they are widely used especially in the traditional machining operations such as milling, turning, grinding and boring.

Mainly, when their composition and properties are considered, cutting fluids can be categorized as four types, including: straight oils, water-soluble oils, synthetics, and semi synthetics [37]. Pure oils are petroleum-based, water soluble cutting fluids use petroleum-based oils. Synthetic cutting fluids contain complex organic compounds and are used with water. While the water concentration of the cutting fluids is usually 5%, the ratio can differ in the range of 1% to 20% [38]. Cutting fluids can also contain or be used with multiple additives such as corrosion inhibitors, antioxidants, emulsifiers, bactericides etc. for serving their specific purposes or satisfying certain standards. The application of cutting fluids to the workpiece - cutting tool contact area is usually done by a nozzle using jet application or by flooding workpiece and cutting tool with cutting fluid by multiple nozzles.

As briefly mentioned earlier, cutting fluids mainly performs three major functions: lubrication, cooling, and transportation of chips from the cutting zone. Also, thanks to the additives cutting fluids contain, they also function as a protection against corrosion and oxidation of the cutting tool, resulting in improved tool life [39]. Improvement of the tool life leads to an increase of product quality. Additionally, as the tools usage times increase, the tool change time interval also increases which leads to saving time and increasing productivity. Lubricating characteristics of cutting fluids results with the reduction of friction in cutting zone, cutting forces, tool wear and built-up edge formation [40]. Consequently, a decrease in surface roughness of the workpiece and energy consumption can be achieved, and increasing speeds or feed values may become possible, resulting in improved productivity. The cooling function of cutting fluids benefits the metal cutting operation by transferring the heat further from the cutting zone which leads to lowered temperatures of the workpiece and the cutting tool. Lastly, with the high-pressure fluid delivery, the chips can be pushed away from the workpiece and cutting tool, therefore it can lower the possible degradation of surface quality through chip embedding [41].

Cutting fluids having multiple functions that contribute to the overall machining operations, leads to a huge amount of usage in metal cutting industries. In machining, CCF usage method is called flooded lubrication or wet machining. This method adapts the coolant-lubricant usage in a controlled manner at various places of the tool chip interface with multiple nozzles and floods both the workpiece and cutting tool. Since the flow rates are high, the cutting fluid usage usually is in the range of 8-10 liters per minute [42]. While the cooling and lubricating capability is satisfactory in flooded lubrication, there are several problems caused by the usage of cutting fluids including the environmental pollution, cost of the CCF and health and safety hazards for workers.

The number of workers that are exposed to the CCF is estimated to be 1.2 million [43]. The exposition can happen in various ways. Firstly, CCF can contact the skin during handling of the parts covered with it even while using gloves. It is possible for CCF to enter the bloodstream of a worker through an existing cut or wound. In such situations, if hands are not properly cleaned, it is possible for CCF to enter the body through the mouth while eating [35]. By their nature, some mineral oils are carcinogens and prolonged exposures to CCF that contain such mineral oils may result with skin cancer [34]. Lastly and mostly, CCF enters the body as a result of inhalation of its mist or vapor. Extensive exposure to cutting fluids may result with several health and safety problems, such as skin infection and respiratory diseases including pneumonia and lung cancer [44]. These negative effects lead several countries to update their laws and regulations and therefore limit the amount of cutting fluid used or ban petroleum-based fluids [35].

From an economic standpoint, the cost of both the CCF and their disposal also has a significant impact. Cutting fluids are thought to be responsible for 7-17% of the overall manufacturing costs [45]. Though this statistic can increase to 20-30% when it comes to machining of difficult to cut materials such as Inconel 718 [46]. Maintenance and disposal of CCF are responsible for most of the cutting fluid related costs. Since the cutting fluids contain different chemical additives and mineral oils, they are not suitable for direct disposal into the environment [35]. Treatment is required prior to disposal, which is highly expensive [47].

The combined drawbacks of CCF lead to a search for alternative techniques in machining. As a result, different methods such as dry machining, cryogenic cooling and MQL are introduced in machining scenery with the aim of making the operations more environmentally safe and sustainable. Each of these alternatives stands out with their unique features.

2.3 Alternative Methods to CCF Machining

2.3.1 Dry Machining

Dry cutting offers the advantage of being independent from cutting fluids. Since cutting fluid is not a requirement, the machining processes that performed under dry cutting conditions result with no pollution nor GHG emissions related to production or waste management of cutting fluids. The main advantages of this method can be listed as [48]:

- No water or air pollution, therefore safer operation environment in terms of skin contact and respiratory damage.
- Reduced costs and energy for the cleaning of lubricant residues on the machined parts.

Without the utilization of cutting fluids, dry cutting method can utilize alternative approaches for improving the metal cutting operations. Mainly, surface modifications such as utilization of coating or geometrical modifications of the cutting tool can be done for increasing the machining performance, resulting lower cutting forces and therefore lower power consumption [49].

Although dry machining is considered an environmentally friendly alternative due to the absence of fluid use, it has a major disadvantage: as previously mentioned, it cannot provide the necessary cooling and lubrication due to the friction that occurs between the tool and chip during cutting. For this reason, it is not commonly used [50].

2.3.2 Cryogenic Machining

Cryogenic machining adapts the application of cryogenic gases for cooling the cutting zone. The term cryogenic is used for performing processes in extremely low temperatures which is below -150°C [51]. The origin of this term comes from the Greek word “κρύος” – “Kryos” which means “cold” [52]. Several gases including Hydrogen, Oxygen, Nitrogen, Neon and Helium are suitable for such usage with liquid carbon dioxide (LCO_2) and Liquid Nitrogen (LN_2) being the most popular options

[53]. The usage of cryogenics in machining can be divided as two; cryo-processing of tools and cryo-processing of the workpiece. While cryogenic machining approach uses cryogens directly to the cutting zone to reduce heat and tool wear, cryo-processing of the tool differs by applying cryogenic treatment to the cutting tool to increase its resistance before the machining operations. Same principles are also followed in cryo-processing of the workpiece with the aim of improving its machinability, earlier to machining operations. By removing heat from the cutting area, cryogenic fluids have the primary benefit of evaporating at atmospheric conditions. These fluids' inert nature prevents them from producing any harmful emissions, making this technique a good option in terms of sustainability [54].

Although cryogenic machining offers excellent cooling and can reduce tool wear, it is not always beneficial due to its high cost and complex equipment requirements. The system needs specialized storage and delivery infrastructure, making it difficult to implement in standard machining setups. Additionally, it is not universally effective across all materials and cutting conditions. Safety concerns and limited environmental gains also hinder its widespread adoption [50].

2.3.3 Minimum Quantity Lubrication

MQL method uses minimal amount of oil for lubrication. The concept behind MQL is that the oil is mixed with compressed air and as a result, the flow generation through the nozzle is in the form of a mist or an aerosol. The contact of mixture provides cooling and lubrication to the cutting zone [55]. MQL is also referred as near dry machining and is originated to address the drawbacks of flood cooling and dry machining and to maintain both ecological and financial balance necessary for the sustainability of processes, products, economy and environment. This method referred as “minimum quantity lubrication” first time in 1993 by Weck and Koch related to the lubrication of the bearings though in metal cutting, MQL was firstly applied in a grinding process and subsequently on the other machining processes [7]. The flow rate or fluid consumption during MQL process varies from 2-500 ml/hr which can be up to 10.000 times less than the conventional flood lubrication [56][57].

MQL is generally considered as the better method in terms of performance compared to dry machining, especially in cases of high-speed machining or machining of materials with low machinability characteristics. From the machining performance perspective, since utilization of geometrically modified or coated cutting tools are not limited to dry machining and are also available to use with MQL, generally it is safe to assume MQL to perform better [15]. When considering high speed machining, significant amount of heat is generated in the cutting zone during the operations. Nickel based alloys, or more specifically in the scope of this study Inconel 718, show tendency to work harden during the increased temperatures, tool life also is significantly dependent on the working temperatures [10]. Past studies show that chip formation on the workpiece and cutting tool and clogging of the chips can cause further problems when dry machining is utilized during such cases [58]. MQL should be the preference.

The system behind the MQL mainly consists of five parts: a fluid tank, air compressor, pipeline, nozzle and lastly flow control system [59]. The usage of MQL process can be divided as internal and external applications. In external systems, the oil and compressed air either can be transmitted and applied respectively or in a form of mixture through an external nozzle. In interval systems, the passage of oil and compressed air mist is through a specially designed spindle and tool holders without an additional nozzle. The transmission mode of interval systems is divided as single and dual channel modes. Single channel transmits the compressed air and oil in a form of mixture while dual channel transmits them respectively and combines them at the front of the tool. External systems are generally preferred for the application of turning and milling and internal systems are more suitable for drilling, reaming and tapping. The schematic representation of MQL systems is shown in Figure 2.4 [60].

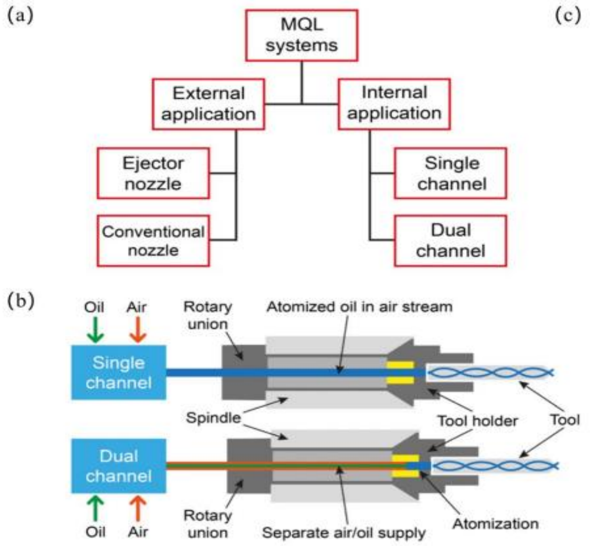


Figure 2.4 (a) - Types of MQL systems (b) - Schematic representation of internal MQL systems (c) - Schematic representation of external MQL systems [60]

Cutting fluid utilization is necessary for all cooling-lubrication methods. Recent studies reported that, when compared to CCF, MQL results as the more sustainable alternative in terms of effects to environment and exposed worker health as the mist generated by MQL reduces the total pollution. Moretti et al. compared MQL with flood lubrication and reported a 67.5% reduction in resultant pollution due to lower oil consumption [61]. Similar results have been reported by Lopes et al. with 68% reduction in pollution in utilization of MQL compared to flood lubrication [62]. MQL supports utilization of biodegradable and eco-friendly cutting fluids. The term “Eco-friendly” is used for cutting fluids that are non-toxic and don’t pollute the environment. Cutting fluids that contain Ammonia Borohydride (amines), Sulfur, Zinc, Chlorine or additives that contain Benzopyrene are considered harmful, thus are not considered as eco-friendly [63]. Lubricant base stocks that are available on the market are primarily mineral oil based, polyalkylene glycols, polyalphaolefins and other synthetic esters derived from petrochemicals [64].

Currently, there are five primary biodegradable base stocks: highly oleic vegetable oils (HOVOs) that are high in monounsaturated fats, polyalkylene glycols (PAG’s), low viscosity polyalphaolefins (PAOs), dibasic acid esters or diesters (DE’s) and polyol esters (PE's) [64]. Among these, polyol esters stand out as biodegradable, hydrolytically stable compounds suitable for various applications, including aerospace, automotive, metalworking fluids, fire-resistant hydraulic fluids, marine hydraulic fluids, rolling oils, food-grade lubricants and transformer fluids [65]. Vegetable oils such as sunflower, rapeseed, soybean, olive, castor, and palm oil have been extensively studied for their renewability and high biodegradability in developing sustainable biolubricants [66]. However, as lubricant performance demands increase, vegetable oil-based lubricants face limitations such as poor thermal and oxidative stability, inadequate fluidity at low temperatures, and a narrow viscosity range, making them unsuitable for modern industrial applications. In response, synthetic ester oils have gained widespread adoption due to their superior low-temperature performance, viscosity stability, and excellent friction-reducing and anti-wear properties [67].

The performance of any machining operation is dependent on the usage and type of cutting fluids. In the cases of difficult-to-cut materials such as Inconel 718, the variation in performance is more prominent. Using different cutting fluids shows different results due to each of the fluid containing their own characteristics including lubrication efficiency, thermal stability and viscosity. Selection of proper cutting fluids is crucial for the optimization of the machining processes regardless of the alternative machining methods that use any form of coolants such as CCF or MQL. Viscosity of MQL oils is crucial for the tendency of forming a stable lubricating film on the workpiece and the cutting tool. Oils with appropriate viscosity provide better lubrication [68]. Thermal stability is a substantial property of MQL oil for managing the heat generated during machining. Inconel 718 generates heat significantly because of its low thermal conductivity and high strength. MQL oils with superior thermal conductivity help absorb and disperse this heat efficiently, reducing the risk of thermal damage to both the tool and workpiece [69]. Oils that show greater lubrication can reduce the tendency of material adhesion to the cutting tool, preventing built-up edge formation and ensuring better surface quality. Inadequate lubrication can lead to increased friction, higher cutting forces, and accelerated tool wear, compromising the efficiency and quality of the machining process [70]. Selecting the proper MQL oil is necessary to achieve optimal machining performance and extend tool life. Different MQL oils have varying compositions and additives, which influence their lubrication and cooling capabilities. The proper selection of MQL oils not only enhances machining performance but also contributes to sustainable manufacturing practices. By choosing oils that offer effective lubrication and cooling, manufacturers can reduce tool wear, improve surface finish, and minimize environmental impact due to lower fluid consumption and better biodegradability of the oils used.

In recent years, the usage of MQL has started to be combined with various methods. While these MQL methods lack in terms of research done in literature compared to traditional usage, they show a promising future.

2.3.3.1 Electrostatic Minimum Quantity Lubrication

Electrostatic Minimum Quantity Lubrication (EMQL) is a modification of conventional MQL. The fundamental principle of EMQL is based on the attraction of opposite charges. In the same principle as MQL, EMQL also benefits from the usage of lubricant droplets, however with the addition of electrical charge [71]. For the electrical charging of lubricant droplets, high voltage direct current is utilized. Consequently, additional electromagnetic force occurs which directs the charged droplets to the grounded cutting tool – workpiece, therefore improving the overall lubrication [72]. Depending on the polarity of the charged droplets, free electrons can either be attracted to or pushed from the surface of the cutting tool. When negatively charged droplets are sprayed, they push the electrons away from the surface of the tool and therefore make the positively charged tool. The result of this action is known as mirror effect [73]. The attraction between positive and negative charges leads to the adhesion of oil to the tool. The principle of mirror effect during the usage of EMQL is shown in Figure 2.5 [72].

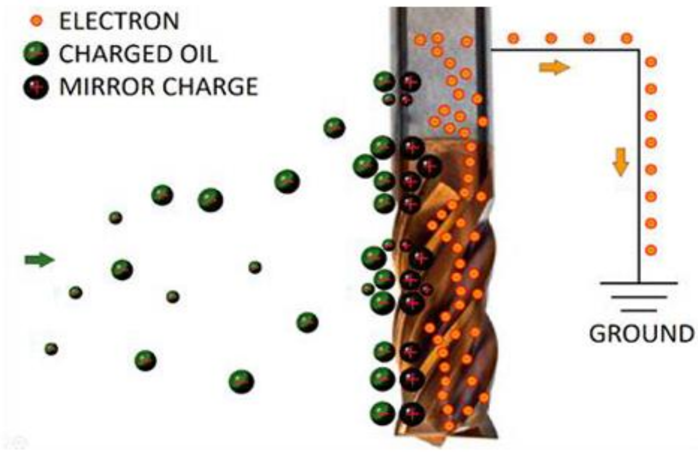


Figure 2.5 Representative image for mirror effect during EMQL [72]

Even though EMQL can offer improved lubrication by electrically charging the lubricant particles, it also has several limitations. It requires precise control of electrical parameters and environmental conditions (e.g., humidity), which can complicate setup and consistency. The system can be sensitive to contamination and grounding issues, affecting performance. Additionally, the initial investment and maintenance costs are higher compared to conventional MQL systems, limiting its broader industrial use.

2.3.3.2 Cryogenic MQL

Cryogenic machining and MQL both are recognized as sustainable alternative machining methods. While there have been many studies with the aim of measuring the effectiveness of these methods in reducing rapid tool wear and enhancing the surface quality of machined materials during the metal-cutting process, recently, there have been some studies that proposed the combined application of cryogenics and MQL can improve machining [74]. The common conclusion of these studies is that the application of MQL and cryogenics simultaneously is the achieving of greater surface integrity and longer tool life [75][76].

As the name implies, Cryo-MQL lubrication is a precise fusion of MQL and cryogenic application, two environmentally friendly machining lubrication/cooling methods. This method is among the best lubricating solutions for materials that are difficult to cut, according to the literature [77][78]. By supplying a sufficient lubricating film between the tool-work and tool-chip interfaces, cryo-MQL lubrication lowers the cutting zone temperature and maintains the tool's functional properties. As a result, tool wear is decreased and surface roughness is lowered. This technique, illustrated in Figure 2.6 has been used by Zou et al. [79] to explain the combined impact of cooling and lubricating simultaneously.

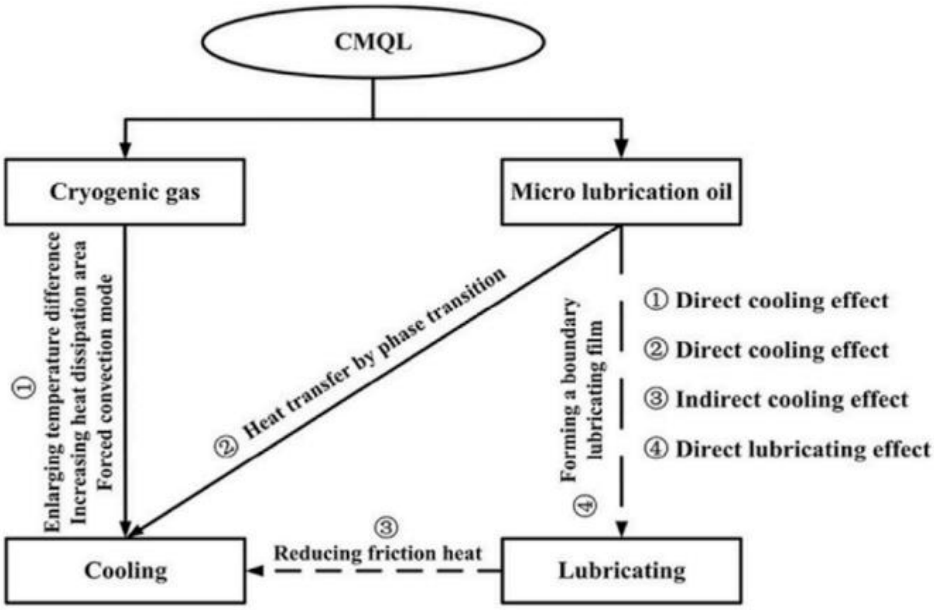


Figure 2.6 Schematic of lubrication and cooling mechanisms in hybrid lubrication [79]

In their study, the usage of cryogenic gas created a mechanism of forced convection in Cryo-MQL and therefore resulted with direct cooling which reduced the temperature in the cutting zone. Additional to the application of cryogenics, the usage of micro-lubricating oils in CMQL improves cooling and lubrication efficiency. This technique uses convection to transport heat and phase transformation to offer direct cooling. Reducing the frictional heat also results in indirect cooling. Direct cooling also occurs as the resultant interaction forms a lubricating boundary film at the cutting zone [79].

There are multiple types of cryogens that can be combined with MQL under the hybrid lubrication technique, past studies include liquid nitrogen (LN2) [80], liquid carbon (LCO2) [81], supercritical carbon dioxide (SCO2) which has properties of both a liquid and a gas phase and is above it’s critical pressure and temperature, dry ice [82] and cryogenic air paired with MQL [83].

Although Cryo-MQL offers enhanced cooling and lubrication, its high cost and system complexity limit its widespread use. It requires precise coordination between cryogenic fluid and lubricant delivery, often demanding specialized equipment and machine modifications. The method is not universally effective across all materials or operations. Additionally, handling cryogenic fluids involves strict safety protocols, which can further complicate implementation.

2.3.3.3 Nanofluid MQL

Another alternative approach to further enhancing the efficiency of MQL is the application of nanofluids. Nanofluid-MQL (NMQL) technique, which involves introducing nanoparticles into the base fluid used in the MQL system. Nanofluid mixture consists of a base cutting fluid which can be oil, water, ethylene glycol and so on and nanometer sized (generally <100 nm) particles that include metallic, non-metallic, carbide, oxide, ceramics, carbonic or mixture of the multiple. The addition of nanoparticles contributes to the fluid by forming distinct properties for the mixture due to their smaller size and higher surface area [84]. This method is designed to improve the overall performance output of the MQL [85]. The key goal of NMQL is to develop a nanofluid with enhanced tribological and thermo-physical properties compared to the original base fluid by incorporating nanoparticles [86]. The outcome of utilizing NMQL depends on multiple factors including the shape, size, type, pH value, thermal conductivity and concentration of the nanoparticles as well as the type and characteristics of base fluid. Addition of nanoparticles such as metals, metal oxides, carbon materials, metal carbides, and metal nitrides to base fluids considerably enhance the thermal conductivity and therefore heat-conducting capability of the base fluid [87]. It is observed in the literature that across multiple traditional machining operations, implementation of NMQL with right parameters results with improved surface finish, tool life and lowered tool wear, the tool-workpiece interface temperature, cutting forces – power consumption when compared to both traditional and sustainable cooling methods [88].

Nanofluids are generally produced using either a two-step or a single-step method. In the two-step approach, nanoparticles are first synthesized through chemical or physical processes, then dispersed into a base fluid using methods such as ultrasonic homogenization, magnetic stirring, high-shear mixing, homogenization, or ball milling. This technique is widely adopted due to its cost-effectiveness and practicality [84]. To improve the dispersion and stability of nanoparticles, especially at lower temperatures, surfactants are often added. Alternatively, the single-step method synthesizes nanoparticles and disperses them directly into the base fluid in a single, integrated process, minimizing issues related to agglomeration and improving uniformity.

Additionally, Hybrid-NMQL (HNMQL) represents a more advanced version of NMQL, leveraging the combined advantages of multiple types of nanoparticles [89]. In this implementation, the dispersion of nanoparticles is formed either as a mixture or compounded. However, utilization of more than one type of particle is a challenging aspect of HNMQL. Maintaining long-term stability becomes difficult when dealing with hybrid nanofluids. This is primarily due to the differing suspension characteristics of two distinct types of nanoparticles, as opposed to a single-component system. To achieve a synergistic enhancement in thermal performance, careful consideration must be given to the combination of nanoparticles—specifically their type, shape, and size to ensure compatibility and effective dispersion[90][91]. Commonly utilized base fluids, nanoparticles and hybrid nanofluids is shown in Table 2.1.

Table 2.1 Hybrid nanofluid with frequently used base fluids and nanoparticles [84]

Base Fluids (BF)	**Combination of Nanoparticles**	**Hybrid Nanofluid**
• Water • Mineral Oils • Ethylene-Glycol • Vegetable Oils • Acetone • Synthetic Oils • Semi-synthetic Oils • Gases • Fatty Oils	• Metals (Ag, Ni, Cu, Au) • Metal Oxides (CuO, Al_2O_3, TiO2, Fe_3O_4, SiO_2, ZrO_2) • Carbon Materials (Graphite, CNT, MWCNT, SWCNT) • Metal Nitrides (TiN, ZrN, CrN) • Metal Carbides and Sulphurides (TiC, SiC, B_4C, MoS_2)	• Combination of Nanoparticles + Base fluids (BF) • Al_2O_3+GnP+BF • CuO+TiO_2+BF • FE_3O_4+SiC+BF • SiO_2+Diamond+BF • ZrO_2+CNTs+BF • Al_2O_3+CNTs+BF • SiO_2+GnP+BF

2.4 MQL Studies on Inconel 718 Machining

Past studies regarding the utilization of both MQL technique and Inconel 718 material showed several advantages of MQL compared to the other machining conditions. Kamala and Obikawa [92] compared MQL, CCF and dry machining of Inconel 718 with utilization of CVD and PVD coated tools. Their study utilized a biodegradable synthetic ester oil and reported that MQL resulted with better surface finish in each coating when compared to wet cutting and the usage of MQL significantly improved the tool life when compared to dry machining. Sivaiah et al. [93] implemented MQL in turning of Inconel 718 using emulsion-based flood cooling 1:20 soluble oil and reported improvements in surface finish and reduction of the tool wear compared to dry machining Saleem and Mehmood [94] utilized TiAlN PVD coated cutting tools and environmentally friendly, sunflower and castor oils for MQL in their study and compared them with dry environment in terms of tool wear and surface roughness. According to their report, in the same conditions as dry environment, sunflower oiled MQL resulted 26% and 52% better respectively. Zhang et al. [95] applied end milling to Inconel 718 using coated tools under dry environment and vegetable oil equipped MQL with the focus of tool wear and cutting forces measurement. In their experiment, MQL with a biodegradable vegetable oil has resulted with 57% more tool life compared to dry machining. Khanna et al. [96] studied turning of Inconel 718 and TI6Al4V in terms of conventional and ultrasonic assisted conditions and implemented sustainability alternatives to each technique. Their findings showed that the combination of ultrasonic assist and MQL results with improved tool life and surface roughness when compared to dry and wet machining. In their experiment, canola oil is used for MQL. They also reported Ti6Al4V emits roughly 40% less carbon than Inconel 718 in all conditions due to Inconel 718 having less machinability and therefore resulting with higher carbon emissions. Halim et al. [97] made a comparison between high-speed milling of Inconel 718 under MQL, dry, and cryogenic conditions. Their results showed MQL having slightly higher cutting force than cryogenic with a ratio of 5.2%. While MQL was in between dry and cryogenic in terms of surface roughness, it extended the tool life 67.2% longer with the maximum volume of material removal when compared to cryogenic. It's lubrication effect reflected more than the cooling effect of cryogenic in terms of tool wear rate. This study used synthetic mist oil for MQL. Kaynak [98] also compared the three conditions in turning and experimented on cutting speeds of 60m/min and 120m/min. His experiment resulted as MQL having the lowest cutting force in each direction at low speed and largest at high speed. While surface roughness levels of cryogenic were better than dry and MQL at high speed, they were very similar with MQL and considerably better than dry at low speed. Tebaldo et al. [99] studied sustainable turning of Inconel 718 and compared MQL with dry, wet and cryogenic environment. Their reports suggested that all conditions resulted with negligible cutting force differences and MQL showed similar tool life to wet and proved to be the best option in terms of cost and environmental impact. Biodegradable, non-toxic oil is used for MQL. Turning experiment of Inconel 718 done by Danish et al. [100] showed MQL reduces surface roughness by 23.2% over dry machining. As compared to dry, total energy consumption was reduced 10% respectively at 100 m/min of cutting speed. For the cutting speed of 200 m/min observations were also similar.

2.4.1 Objective of Study

As observed across a wide range of studies in literature, the application of MQL has been shown to consistently deliver superior performance in machining operations when compared to CCF or dry cutting methods. These improvements are most notably reflected in reduced cutting forces, improved surface finish, and extended tool life, all of which are critical parameters in achieving efficient and sustainable manufacturing. The effectiveness of MQL, however, is not solely dependent on the delivery method but is also significantly influenced by the properties of the base fluid used. Different base oils possess varying chemical compositions, viscosities, and thermal conductivities, all of which can lead to markedly different outcomes in machining performance. Therefore, selecting an appropriate base fluid is essential to fully harness the potential of MQL in advanced manufacturing applications.

Despite the acknowledged importance of base fluid selection, a considerable portion of the existing literature has primarily concentrated on a limited set of oils—often mineral or vegetable-based—without adequately exploring the impact of their molecular structures on lubrication behavior and overall performance. This narrow scope has resulted in a gap in understanding regarding the role of chemical structure in influencing heat dissipation, lubrication effectiveness, and ultimately, sustainability in machining. To address this research gap, the present study investigates the use of several polyol and polymeric ester-based oils, each with distinct chemical structures, during the slot milling of Inconel 718.

Although several studies have investigated the machining of Inconel 718 under various lubrication conditions including dry, flood, and MQL techniques, the literature remains limited in terms of providing a comprehensive environmental performance analysis, especially when it comes to slot milling operations. Very few studies incorporate a detailed assessment of carbon emissions associated with the use of different MQL base fluids, despite the growing emphasis on sustainability and eco-efficiency in modern manufacturing. In this context, the current study not only evaluates traditional performance metrics such as cutting forces, surface roughness, and surface topography but also includes a full-scale carbon emission analysis. This holistic approach enables a more informed evaluation of both the technical and environmental implications of using chemically diverse ester-based lubricants in the MQL-assisted machining of Inconel 718.

CHAPTER 3

METHODOLOGY

3.1 Machining Conditions

Three samples of age-hardened Inconel 718 workpiece material is used during the experiments with dimensions of 87 mm × 55 mm × 6 mm, hardness of 37 (± 1) HRc and a yield strength of 1035 (± 5) MPa. Before conducting the experiments, all workpiece surfaces were face milled to remove the original outer layer in order to obtain flatness. Mechanical properties and chemical composition of the material are given in Table 3.1 and Table 3.2 respectively [101]. Akira Seiki SR3XP CNC milling center was used for conducting the slot milling experiments.

Table 3.1 Typical mechanical properties of Inconel 718 at room temperature [101]

Tensile strength (MPa)	**Yield strength (MPa)**	**Young's modulus (GPa)**	**Hardness (HRc)**
1240	**1036**	**206**	**36**

Table 3.2 Chemical composition of Inconel 718 [102]

Element	Ni	Cr	Nb	Mo	Ti	Al	Co	Mn	Cu	P	S	Fe
Wt % min.	50	17	4.75	2.8	0.65	0.2	≤0.35	≤0.35	≤0.3	≤0.015	≤0.015	17
Wt % max.	55	21	5.50	3.3	1.15	0.8						

Iscar brand EC-A4 100-22C10-72 model four-flute solid carbide end mill coated with TiAlN were used in all experiments. The specification of the cutting tool is provided in Table 3.3 [102]. The cutting conditions, were kept constant for all experiments which include cutting speed of 50 m/min, feed rate of 0.05 mm/tooth and depth of cut of 1 mm as shown in Table 3.4. These parameters were determined with respect to recommended ranges from the cutting tool manufacturer, and tap tests were also performed beforehand to identify the stability lobes. (Figure 3.1). Tap testing ensured that the selected values would not induce any chatter which is a considerable problem in the milling process and directly affects the results [103]. To prevent issues related to chatter, the cutting tool underwent tap testing, and the results were analyzed using the CutPro Simulation Software [104]. Initial tests were carried out under dry cutting conditions to capture the cutting sound, using a PCB 130A24 microphone paired with a National Instruments NI-9234 data acquisition system. Signals were processed through the CutPro Data Acquisition Module. Subsequent analysis using Fast Fourier Transform (FFT) showed no evidence of vibrations caused by chatter. Different slots were cut for each experiment, and multiple passes were not made on the same slot. Experiments for each cooling strategy were repeated for 3 times. For the coolant and lubrication strategy, a vegetable-based oil with an 8% oil-water mixing ratio and a flow rate of 50 l/h was employed in CCF experiments. The utilized MQL system is set with two nozzles angled 45 ° and an oil flow rate of 50 ml/h under a pressure of 6 bar.

Table 3.3 Cutting tool specifications [102]

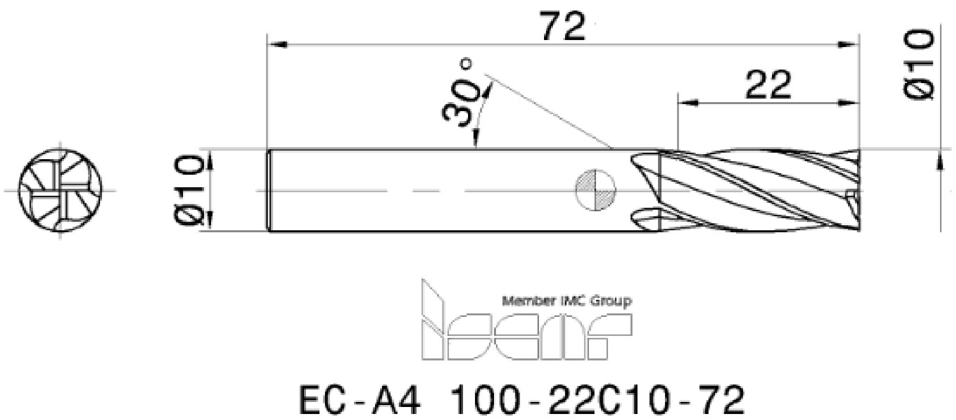


Table 3.4 Design of experiments

Parameters			
Cutting Speed (m/min)	**Feed (mm/tooth)**	**Depth of Cut (mm)**	**Coolant/Lubrication Type**
50	0.05	1	Conventional Cutting Fluid (Flood Cooling)
			Dry Condition
			MQL-1- Trimethylolpropane Trioleate Polyol Ester (TMPTO)
			MQL-2- Polymeric Ester-1 (PE-1)
			MQL-3- Polymeric Ester-2 (PE-2)

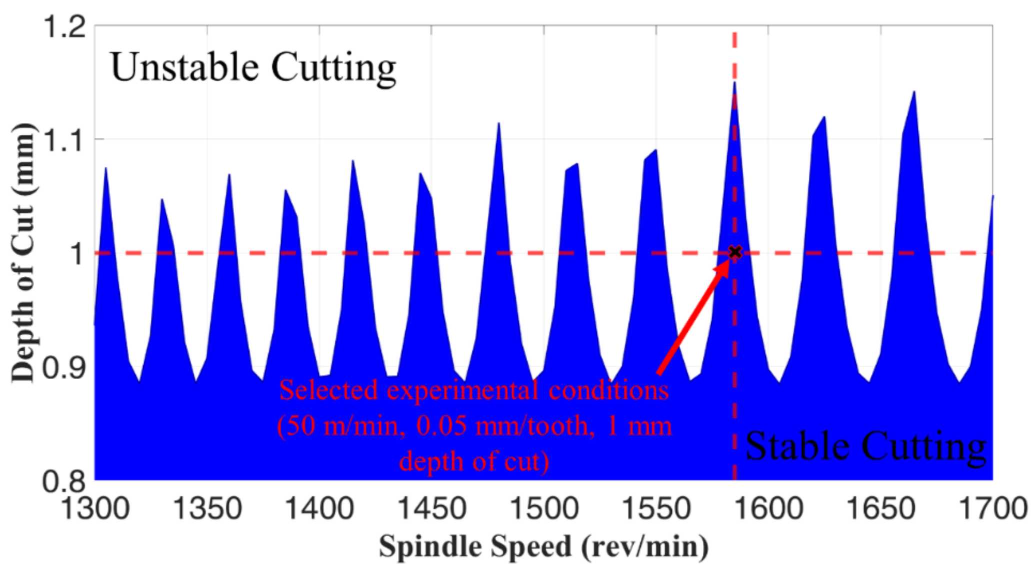


Figure 3.1 Stability lobe diagram

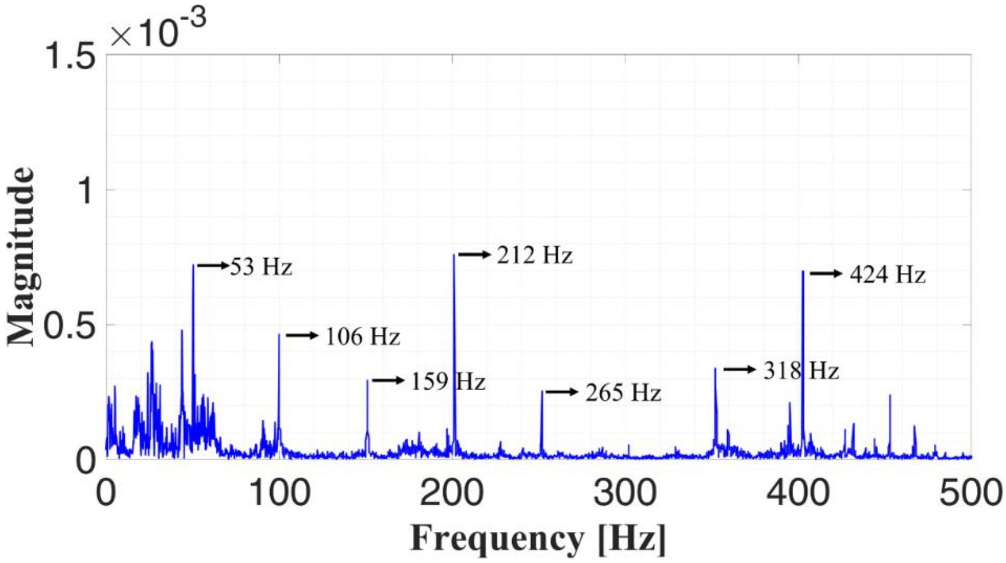


Figure 3.2 FFTs of the measured cutting sound

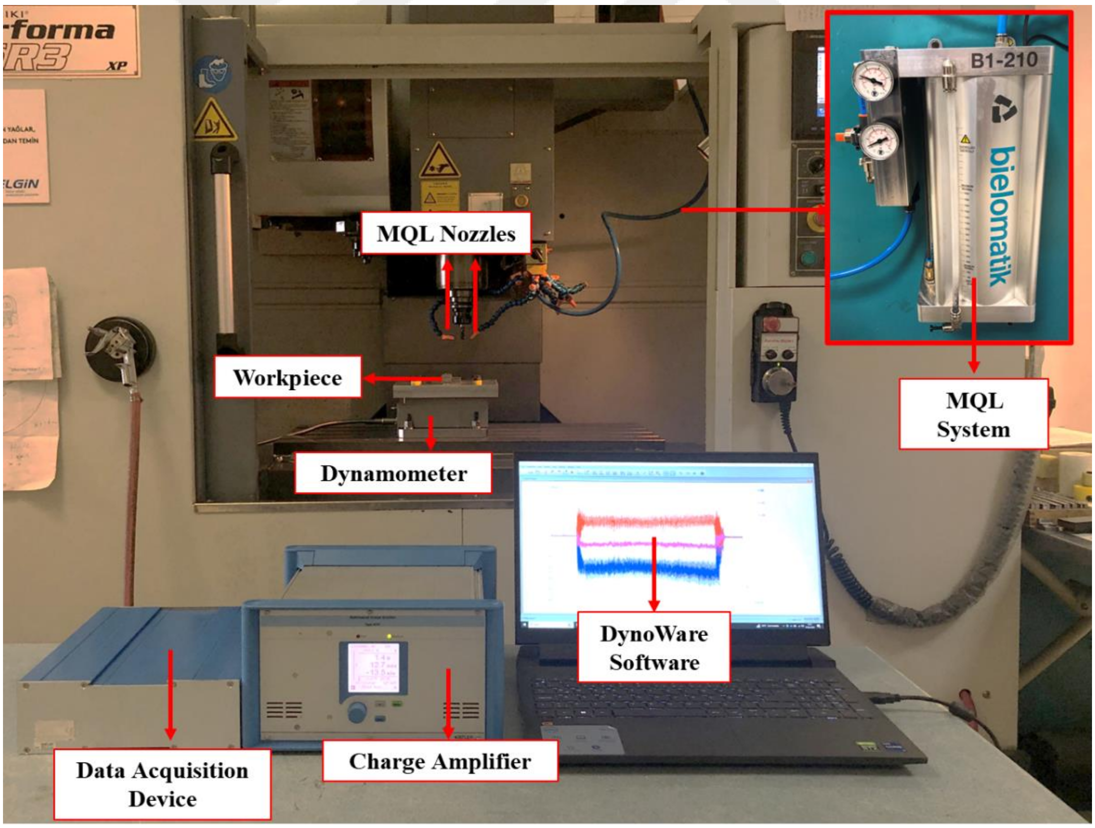


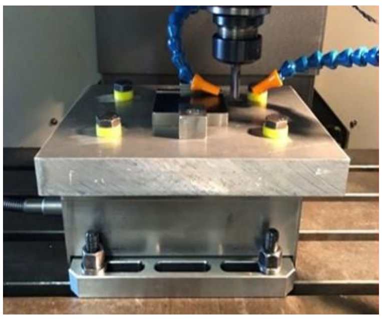
Figure 3.3 Experimental setup

3.2 Measurement Tools and Techniques

The cutting forces are measured by using a dynamometer featuring a three-component piezoelectric quartz crystal (Kistler 9256B), along with a charge amplifier (Kistler 5070) and a data collection system (Kistler 5697A1). The collected data was processed and stored using signal analyzer software (Kistler Dynoware). The sampling frequency of the measurements were set to 100 kHz. The average cutting force during the stable cutting phase was computed, excluding the phases of slot entry and exit.

After the cutting experiments, workpieces cleaned from the lubricant oils on their surfaces using an ultrasonic bath to be prepared for the measurement of 3D surface. 3D surface profile of the mill entrance, exit and middle sections of the slots were captured using the optical 3D surface measurement tool, Alicona InfiniteFocus. In order to ensure consistency of the measured values, three measurements were made. The data from Alicona InfiniteFocus was then evaluated with Gwyddion software [105] to determine the 3D surface topography and areal surface roughness (Sa).

Similar to workpieces, cutting tools were also cleaned from the lubricant oils on their surfaces using an ultrasonic bath to be prepared for the measurement of wear. For the measurement of cutting tool wear, Dino-Lite AM4113T digital microscope is used. With the aim of identifying the tool life for each cutting tool, flank wear of each cutting tool is measured. The utilized tools are shown in Figure 3.4.



Dynamometer

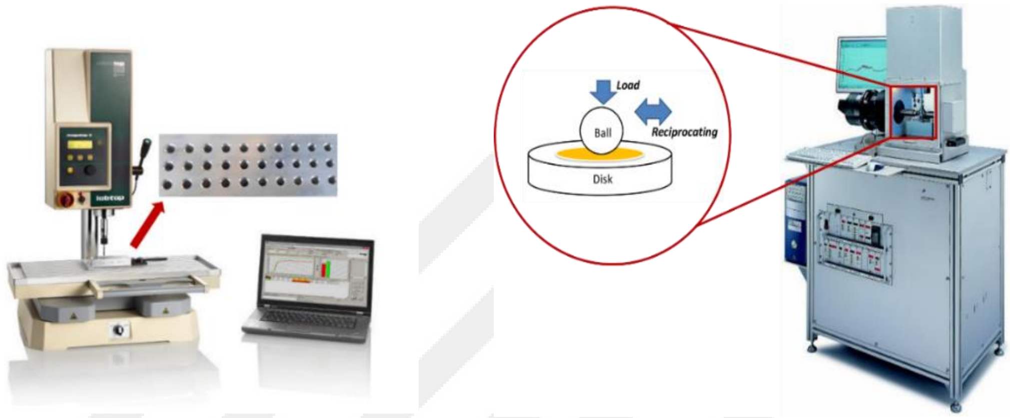
Surface Measurement

Optical Microscope [106]

Figure 3.4 Utilized tools

3.3 Coolant / Lubricant Oils

Multiple performance evaluations were done for the coolant/lubricant oils prior to usage in the experiments including, SRV® EP Step Test, The SRV® Wear Test and Tapping Torque Test. Microtap brand MEGATAP II-G8 device was used for the Tapping Torque test, while the Optimol brand SRV® 4 testing device was utilized for SRV® EP Step and Wear tests. The devices that were used during the performance tests are shown in Figure 3.5.



(a) (b)

Figure 3.5 (a) - Tapping torque device [107], (b) - SRV® test device [108]

3.4 Developed MQL Characteristics

To assess the physical and performance characteristics of the developed MQL oils, the obtained data is displayed in Table 3.5 under "Physical properties of the MQL oils" and in

Table 3.7 under "Performance test results of the MQL oils."

Kinematic viscosity plays a vital role in determining the effectiveness of lubricating oils in MQL applications, as it directly influences their performance. It measures a fluid's resistance to flow under gravity. In MQL systems, where lubricants are applied as a mist or aerosol, kinematic viscosity is essential for proper atomization. Oils with lower viscosity enhance atomization, leading to improved distribution across the cutting zone for more effective lubrication and cooling. Additionally, lower viscosity facilitates deeper penetration into the cutting zone, allowing the lubricant to reach the interface between the cutting tool and workpiece. This helps minimize friction and heat buildup, ultimately improving machining efficiency and prolonging tool lifespan. Typically, MQL oils have kinematic viscosity values ranging from 10 to 500 cSt, making them adaptable to various MQL systems.

The Viscosity Index (VI) indicates how viscosity changes with temperature. In MQL machining, a higher VI is preferred as it ensures consistent lubricating properties across various temperatures encountered during operations [109]. Oils with a high VI maintain their viscosity over a broader temperature range, crucial for materials like Inconel 718 that reach high temperatures during processing.

The Total Acid Number (TAN) measures the acidity of an oil. Lower TAN values are preferred in MQL applications to prevent corrosive effects on machine components and tools. Minimizing acidity helps protect against corrosion, prolonging the lifespan of tools and equipment [110]. Therefore, selecting MQL oils with a lower TAN is essential for maintaining the performance and longevity of machining equipment.

Biodegradability is an important characteristic of lubricants used in MQL, as it determines how effectively a substance can decompose into environmentally safe components through natural processes. Since MQL lubricants may contact with the environment, high biodegradability is essential for promoting sustainability. Using biodegradable lubricants helps minimize environmental impact while ensuring compliance with industrial fluid regulations. The tested MQL oils exhibit a biodegradability rate of 99.9%, significantly surpassing the 80% benchmark, highlighting their contribution to eco-friendly machining practices.

Thermal conductivity measures a material’s ability to conduct or transfer heat which is also crucial for oils that are utilized as coolants. Higher thermal conductivity values indicate improved heat removal during the metal cutting process [111]. While the thermal conductivity values of utilized MQL oils are not provided by the supplier, an estimation can be given with respect to literature. In the study done by Bruno et al. [112] various polyol ester based oils utilized and the thermal conductivity values showed results as low as 0.14 W/m·K around room temperature, in the same conditions, Jamil et al. [113] reported thermal conductivity value of 0.16 W/m·K for ester oil. While the utilized MQL oils differ from the ones in the respective studies in terms of their chemical composition, in general their thermal conductivity values can be accepted as better than mineral based or water based oils [114].

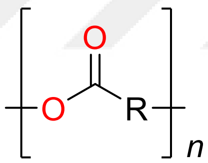
Schwingung, Reibung, and Verschleiß (SRV) Test plays a vital role in assessing oscillating friction and wear properties, helping evaluate how lubricants and materials perform under sliding and oscillating conditions. In MQL applications, this test is particularly useful for determining how well MQL oils reduce friction and wear between the cutting tool and workpiece. Lower wear rates and friction coefficients in SRV testing indicate superior lubrication performance. These results offer key insights into the lubricant's ability to form a protective layer, minimize friction, and reduce wear in the cutting zone. MQL oils that perform well in the SRV test can enhance machining efficiency and prolong tool life. All tested MQL oils successfully meet the required SRV value of 0.500.

The SRV EP (Extreme Pressure) Step Test is used to analyze the extreme pressure resistance and anti-wear characteristics of lubricating oils and greases. In machining and MQL applications, this test determines how well a lubricant can endure high-pressure conditions. The process involves gradually increasing the applied load under sliding and oscillating motion, offering valuable data on the lubricant's ability to minimize wear and maintain effective lubrication under extreme stress. Lubricants with strong extreme pressure properties help protect cutting tools and workpiece surfaces during high-load operations, ultimately improving machining efficiency and extending tool lifespan. This factor is especially crucial when working with Inconel 718, a material that frequently experiences substantial cutting forces. While all tested MQL oils meet the baseline requirement of 400 N in the SRV EP Step Test, MQL-2 surpasses expectations by achieving 500 N, demonstrating exceptional performance and a competitive edge in machining applications.

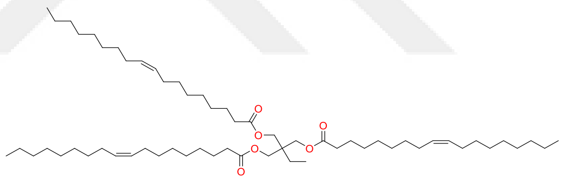
The Tapping Torque Test is used to analyze the lubricating and anti-friction properties of oils and lubricants, particularly in machining operations that involve tapping or threading. This test measures the torque required to tap a threaded hole, offering insights into how well a lubricant reduces friction and enhances the tapping process. In MQL applications, it helps evaluate a lubricant's effectiveness in minimizing friction during tapping. A lower tapping torque signifies better lubrication and reduced friction between the tap and the workpiece material. Lubricants that perform well in this test contribute to smoother tapping operations, extended tool life and reduced wear on both the tool and workpiece. While all tested MQL oils remained below the target threshold of 350 Nm, MQL-2 demonstrated the lowest value, highlighting its competitive advantage.

Table 3.5 Physical properties of the MQL oils

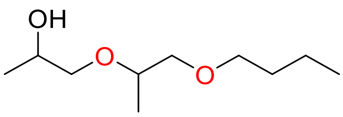
Test, Feature and Unit	Test Method	Target Value	MQL Oils Used in Experiments		
			MQL-1 (TMPTO)	**MQL-2 (PE-1)**	**MQL-3 (PE-2)**
Kinematic Viscosity (40°C, cSt)	ASTM D 445	10-500	98.4	222.42	208.3
Viscosity Index	ASTM D 2270	-	180	221	182
Total Acid Number (TAN) (mg KOH/g)	ASTM D 974	max 5.0	2.0	3.1	1.92
Biodegradability Test	OECD 301 B	min %80	%99.9	%99.9	%99.9



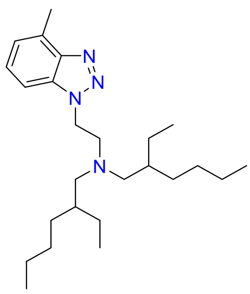
Polymeric Ester (PE)



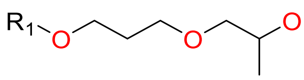
Polyol Ester (TMPTO)



Cooling Agent (CA)



Metal Deactivator (MD)



Emulgator (EM)

Figure 3.6 Molecular structure of the compounds used in the formulation model

Table 3.6 Formulation models applied in the study

Ester Type	Sample composition
Trimethylolpropane Trioleate	TMPTO + Water+ EM+ MD + CA+ Other
Polymeric Ester	PE-1+ Water+ EM+ MD + CA+ Other
Polymeric Ester	PE-2+ Water+ EM+ MD + CA+ Other

Table 3.7 Performance test results of the MQL oils

			MQL Oils Used in Experiments		
Test, Feature and Unit	**Test Method**	**Target Value**	**MQL-1 (TMPTO)**	**MQL-2 (PE-1)**	**MQL-3 (PE-2)**
SRV Wear Test (fmax)	ASTM D 6425	max 0.500	0.195	0.147	0.192
SRV EP Step Test (N)	ASTM D 7421	min 400	400	500	400
Tapping Torque Test (Nm)	ASTM D8288	max 350	142.6	119.6	126

3.5 Machining Performance Parameters

3.5.1 Cutting Force

Cutting force components contribute significantly to energy consumption in machining. Therefore, minimizing and managing these forces is essential for promoting sustainability in manufacturing processes. The cutting force values, encompassing forces from three different axes, are calculated as the resultant cutting force, as shown in Equation (1).

$$F_R = \sqrt{{F_x}^2 + {F_y}^2 + {F_z}^2} \quad (1)$$

While measuring the cutting forces, it is more accurate to exclude the entrance and exit phases of the cutting tools and the measurement should be done by considering the most stable stage of cutting. An example of measured cutting force signals can be seen in Figure 3.7. The average cutting force values of each experiment is determined in “Results and Discussion” section.

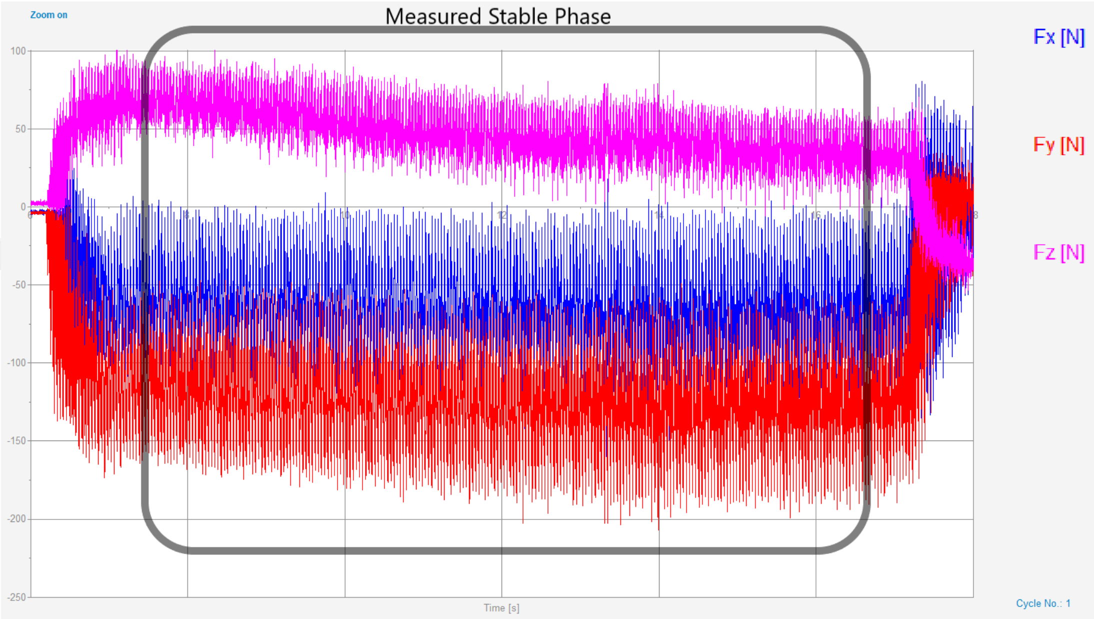


Figure 3.7 Measured cutting force signals (MQL-1)

3.5.2 Surface Quality

The characteristics of solid surfaces play a vital role in surface interactions, as they influence key factors such as actual contact area, friction, wear resistance, and lubrication. Beyond their impact on tribological behavior, surface properties are also essential in various other applications, including optical, electrical, and thermal efficiency, as well as coating adhesion and aesthetic appeal.

Regardless of how they are formed, solid surfaces inherently exhibit deviations from their ideal geometric shape. These imperfections exist at multiple scales, from macroscopic shape variations to microscopic irregularities approaching interatomic distances. Even the most precise machining techniques cannot achieve a perfectly molecularly flat surface on conventional materials.

Surface texture refers to the recurring or random variations from the intended surface, shaping its three-dimensional topography. It encompasses several elements, including roughness, which can range from nano-to microroughness, waviness, in terms of macroroughness, lay, and flaws as shown in Figure 3.8 [115][116].

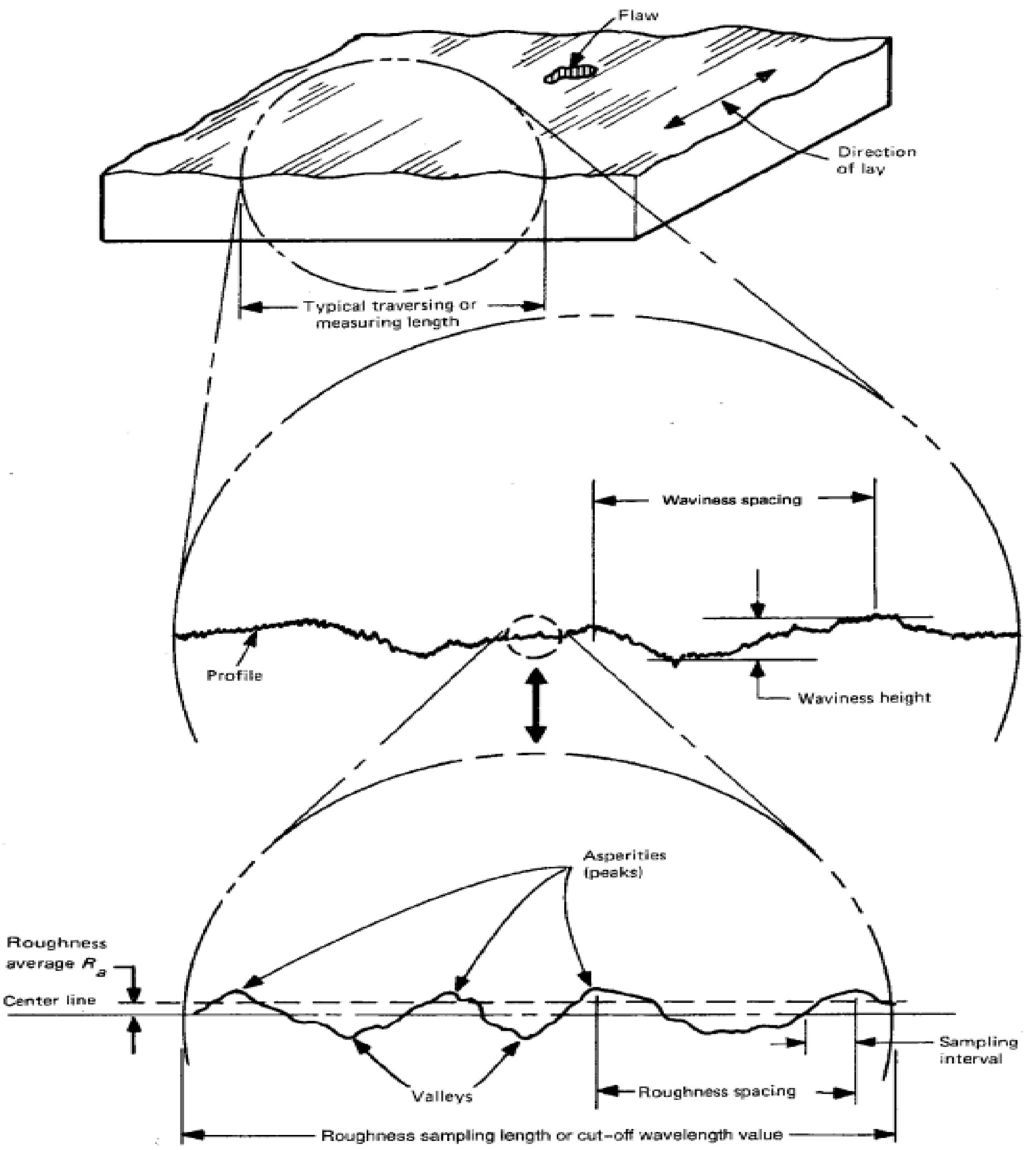


Figure 3.8 Representative display of surface texture [115]

The values of surface quality obtained after machining operations are crucial performance outputs that significantly influence various important parameters such as the need for secondary surface treatments, service quality, and fatigue life of the produced part. In this study, the evaluation of surface quality is conducted through surface roughness and surface topography.

Surface roughness quantifies the degree of smoothness by analyzing microscopic deviations from a surface's ideal form. It is a crucial factor that affects the results of interaction between parts such as the proportional load or stress distribution. Therefore, it is a factor that directly influences the performance and quality of the final product. Additionally, in cases of unsatisfactory surface quality results, additional machining stages may be required which decreases work efficiency and increases the cost. Thus, aiming for low surface roughness is of utmost importance in machining operations. Surface roughness typically describes fluctuations in surface height relative to a defined reference plane. It can be assessed using either a single-line profile or multiple parallel line profiles and generally characterized by the height descriptor standards of either the International Standardization Organization (ISO) and the American National Standards Institute (ANSI). In the experiments, the average areal surface roughness of each slot has been measured firstly by taking the 3D surface profiles from three areas of the slot including the entrance, exit and middle by using Alicona Infinitefocus, the optical 3D surface measurement tool. The data obtained from the 3D surface measurement then evaluated using Gwyddion software to attain the 3D surface topography and areal surface roughness (Sa).

Surface topography refers to the detailed examination and characterization of a material's surface features, including its texture and pattern of irregularities at both the micro and nano scale. It helps in understanding how a surface interacts with its environment, such as in friction, wear, adhesion, or coating performance. It plays a significant role in linking process parameters to the performance of manufactured parts, as it directly affects the longevity of the components. Examining three-dimensional (3D) surface topography helps identify defects, porosities, and assess tribological behavior as well as surface appearance. The resultant surface roughness values and topography images are shown in "Results and Discussion" section of the report.

3.6 Sustainability Assessment

3.6.1 Carbon Emissions in CNC Based Machining

Machining serves as both a primary and secondary process in manufacturing and represents one of the largest shares of production activities, contributing to approximately 70% of the industry's total business volume. As a result, addressing sustainability in machining practices has significant importance [117]. A prominent factor for the measurement of sustainability is the measurement of carbon footprint. Carbon footprint is defined as carbon dioxide equivalent of the greenhouse gases released into the atmosphere as the result of any activity [22]. Greenhouse gases are the group of gases contributing to global warming and climate change. Name origin of the carbon goes back to "carbo" which means "charcoal, coal" in Latin [118]. Between the carbon-based resources that also include oil gas etc. coal is still considered as the main power source for manufacturers and the resulting emissions are responsible for more than half of the total carbon emissions[22].

Carbon Emission Factor (CEF) is a coefficient that describes the rate at which a given activity releases carbon dioxide-equivalent (CO_2e) greenhouse gases (GHGs) into the atmosphere. The activity data and CEF are the major values to calculate the carbon footprint [119]. Carbon dioxide-equivalent (CO_2e) values are calculated by multiplying the emission mass of each greenhouse gas by its Global Warming Potential (GWP) over a 100-year time frame. GWP indicates how much heat a greenhouse gas can retain in the atmosphere compared to carbon dioxide, which is used as the baseline reference. [22]. In Table 3.8, the major GHGs and their respective GWP are provided. The latest values, which are from the Sixth Assessment Report should be considered [120].

As the name suggests, the machining operations that are considered as CNC based, requires utilization of at least one or multiple CNC machines, each with their own set of machine tools, work pieces, fixtures, cutting tools etc. Carbon emission of these systems generally forms indirectly as the result of machine tool operations. Since the usage of electricity or raw materials doesn't directly cause carbon emission production, the generation of such consumables and their resultant carbon emissions need to be considered. Dahmus and Gutowski [121] stated that the analyzing of such systems firstly requires a defined set of system boundaries. Li et. al extended Dahmus's boundary model and adapted for CNC based systems shown in Figure 3.9 [19].

Table 3.8 IPCC GWP values relative to CO_2 [120]

Common chemical name or industrial designation	Chemical Formula	GWP values for 100-year time horizon		
		Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)	Sixth Assessment Report (AR6)
Major Greenhouse Gasses				
Carbon Dioxide	CO_2	1	1	1
Methane - non fossil	CH_4	25	28	27
Methane - fossil	CH_4	N/A	30	29.8
Nitrous oxide	N_2O	298	265	273
Nitrogen trifluoride	NF_3	17.200	16.100	17.400
Sulfur hexafluoride	SF_6	22.800	23.500	24.300

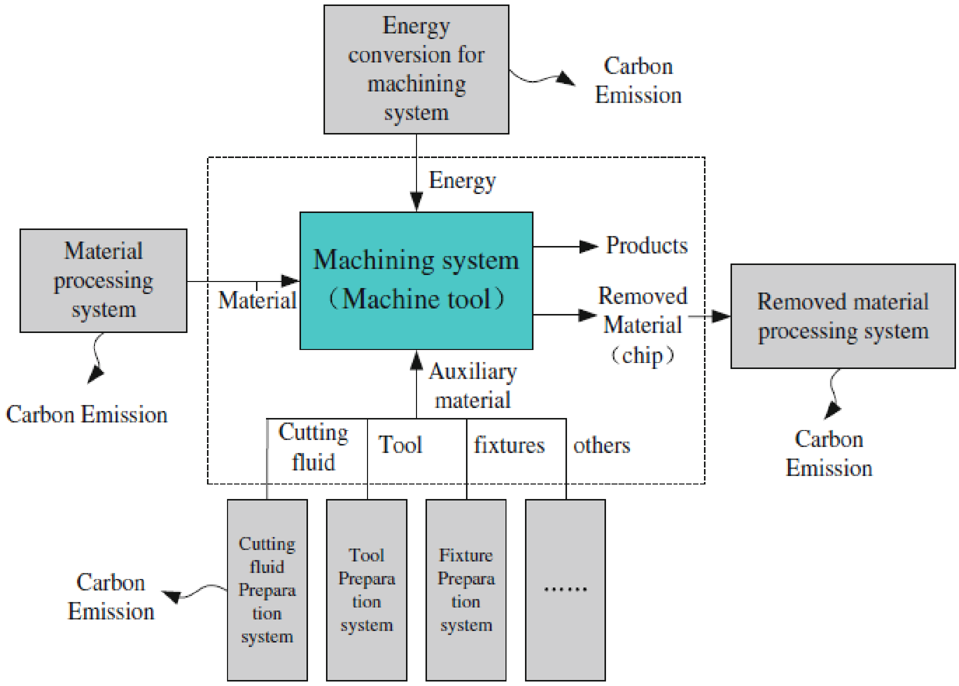


Figure 3.9 Carbon emission boundaries for CNC machining systems [19]

This model is adopted in various research papers and can be considered as the definitive method for examination of carbon emissions in CNC machining operations [122][123][124]. According to this model, the inputs that contribute to carbon emission in machining systems are:

Energy spent; as the result of the electricity generated required during the machining operations,

Material production; since the extraction and preparation of the raw materials including workpiece, auxiliary materials such as cutting tools and coolants are in the utilization of machining, the resulting carbon emissions from production of such materials are also included in the total carbon emissions related to machining.

Chip removal-recycling; while the workpiece material production is included in the calculation of the total carbon emissions, it should be stated that the operation is responsible for only the removed portion of the material. The removed materials are produced in the form of chips. Chips are required to be collected to undergo metal recycling. The energy spent during recycling process leads to a release of carbon emissions and therefore should be included in total carbon emission calculations in machining.

The summation of these factors that contribute to carbon emission can be written as:

$$CE_{total} = CE_{electric} + CE_{c/l} + CE_{tool} + CE_{material} + CE_{chip} \tag{2}$$

Where;

CE_{total} = Total carbon emissions related to complete machining operation

$CE_{electric}$ = Carbon emissions due to electricity consumption

$CE_{c/l}$ = Carbon emissions related to the production of the used coolant - lubricant

CE_{tool} = Carbon emissions related to the production of cutting tool

$CE_{material}$ = Carbon emission related to the production of raw material

CE_{chip} = Carbon emission associated with chip removal

The detailed calculations of each of these factors are obtained with respect to their CEF and activity data.

3.6.1.1 Carbon Emissions of Electricity

The energy usage of a CNC machine tool can be categorized into constant and variable components. Constant energy is typically used during startup processes—such as activating servos, spindle mechanisms, and the coolant pump system—as well as during specific operations like jogging, spindle rotation, and tool changes. In contrast, process energy consumption fluctuates depending on the machine's workload [125]. Since the optimal determination of the energy spent during the startup process and idle time is rather complex without additional equipment such as power testers, this study follows the approach of Singh et al. [126] and includes only the energy spent in process level.

$CE_{electric}$ is a variable that is dependent on the carbon emission factor of electricity ($CEF_{electric}$) which is listed differently for each country and the energy spent during the actual cutting stage of the experiment (E_{cut}). $CEF_{electric}$ for Türkiye is taken as 0.5434 kg/kWh [127].

$$CE_{electric} = CEF_{electric} * E_{cut} \tag{3}$$

E_{cut} is determined by multiplying the cutting power (P_{cut}) and actual cutting time (t_{cut}) as shown in Equation (4). In the experiments, average of t_{cut} recorded is listed as 12 seconds per slot and since each cooling method completed three slots total t_{cut} has taken as 36 seconds.

$$E_{cut} = P_{cut} * t_{cut} \tag{4}$$

P_{cut} is obtained by multiplying the resultant cutting force (F_r) with the cutting speed (V_{cut}) as shown in Equation (4).

$$P_{cut} = \frac{F_r * V_{cut}}{60000} \tag{5}$$

3.6.1.2 Carbon Emissions of the Coolant – Lubricant Oil

The carbon emissions linked to cutting fluid use can be divided in two parts: emissions produced during the manufacturing of the pure mineral oil contained in the cutting fluid (CE_{oil}) and emissions resulting from the disposal of used cutting fluid (CE_{wcl}), as it's shown in Equation (5) [128]. While considering the usage time of the coolant and therefore calculating the total amount of fluid, both machining and air cutting time is included. CEF_{oil} and CEF_{wc} in the equations represent carbon emission factors of cutting fluid production and waste management respectively. CC represents the total amount of cutting fluid and is a variable of flow rate (Q). In the experiments, the adapted flow rate of MQL is 50 ml/h or 0.05 l/h while CCF is 50 l/h. δ is the predetermined cutting fluid concentration that is used for CCF and equals to 0.08. The value of the CEF_{oil} can be calculated with respect to the embodied enegy of the mineral oil (EE_{oil}) and carbon intensity of the mineral oil (EC_{oil}) as shown in Equation (10). EE of oily substances usually is in the range of 41,868 – 42,705 KJ/kg. For the EC of the oily substances, 20 kgC/GJ is accepted [19]. The average of the embodied energy values is adapted for the calculations.

$$CE_{coolant} = CE_{oil} + CE_{wc} \quad (6)$$

$$CE_{oil} = CEF_{oil} * CC \quad (7)$$

$$CE_{wc} = CEF_{wc} * (CC/\delta) \quad (8)$$

$$CC = \frac{(t_{cut} + t_{idle}) * Q}{3600} \quad (9)$$

$$CEF_{oil} = EE_{oil} * EC_{oil} * \frac{44}{12} * d_{oil} \quad (10)$$

Emissions related to waste disposal (CE_{wc}) are only included for the CCF method since MQL only uses a minimal amount of oil and therefore doesn't require any additional waste management process. Since the utilized CCF has a predetermined cutting fluid concentration of 0.08, which means 92% of the CCF is made of water, carbon emission factor of cutting fluid waste disposal (CEF_{wc}) is chosen as the 0.2 kgCO2/L which is the water disposal emission factor [19].

3.6.1.3 Carbon Emissions of the Cutting Tool

Generally, by the logic of a practical workshop, tool life can be described as the time it takes for a cutting tool to fail producing workpieces with the desired dimensions or surface quality. It is dependent on several machining parameters including cutting speed, feed rate, depth of cut, cooling method, coolant etc. However, according to ISO 8688, tool life criterion for milling is accepted as the flank wear occurrence on the cutting tools blades with the average width of 0.3 mm as shown in Figure 3.10 [129].

Tool life (T_{tool}) is one of the parameters that is necessary for the carbon emission calculation related to the production of the cutting tool (CE_{tool}). Other parameters include cutting time (t_{cut}), carbon emission factor of the cutting tool (CEF_{tool}) and mass of the cutting tool (W_{tool}) as shown in equation (11) [19].

$$CE_{tool} = \frac{t_{cut}}{T_{tool}} * CEF_{tool} * W_{tool} \tag{11}$$

CEF_{tool} is dependent on resultant electricity consumption of using cutting tools. Adapted formula for obtaining CEF_{tool} is shown in equation (12). K is the energy consumption constant of the cutting tool and accepted as 1.5 MJ when embodied energy is excluded and only the tool production part of the energy spent is considered [130]. Weight of the utilized cutting tool (W_{tool}) is 0.0697 kg.

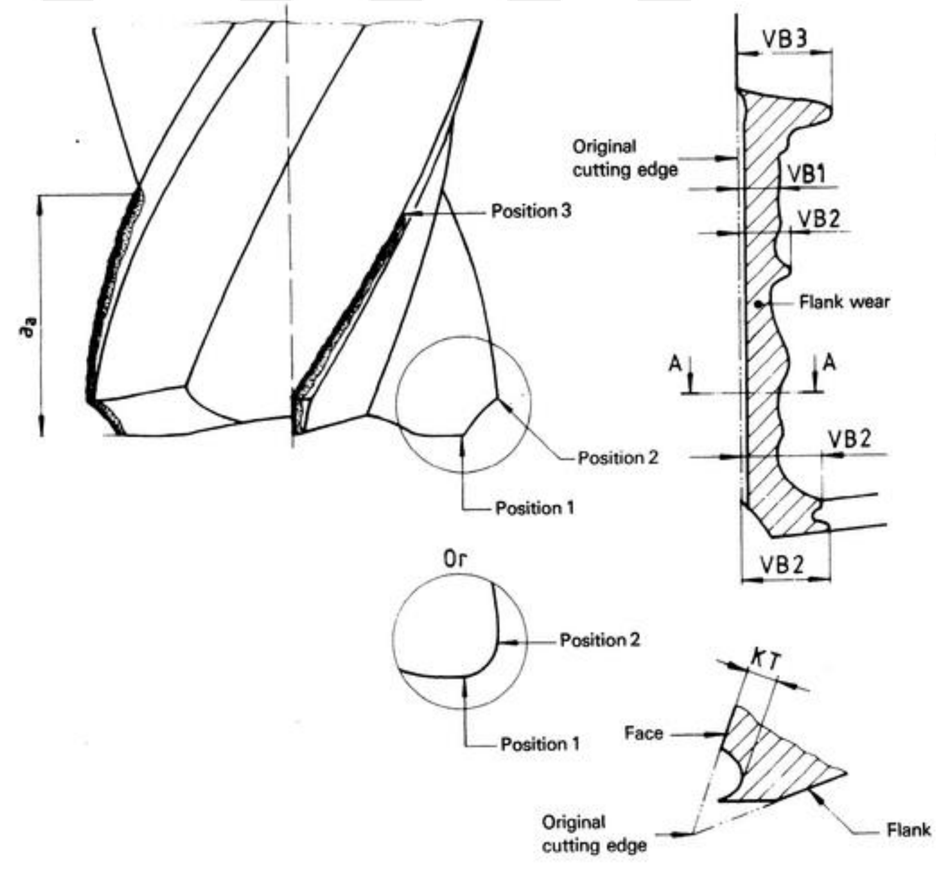
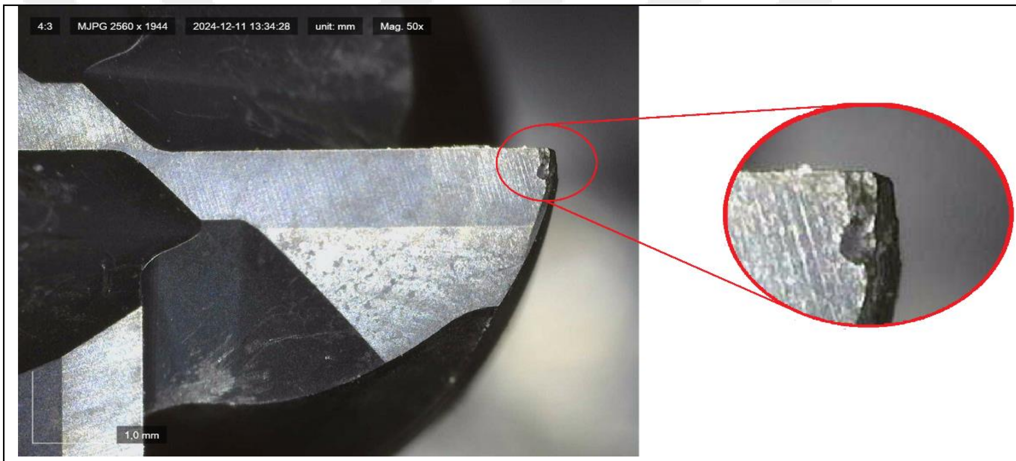


Figure 3.10 Wear on end milling cutters [129]

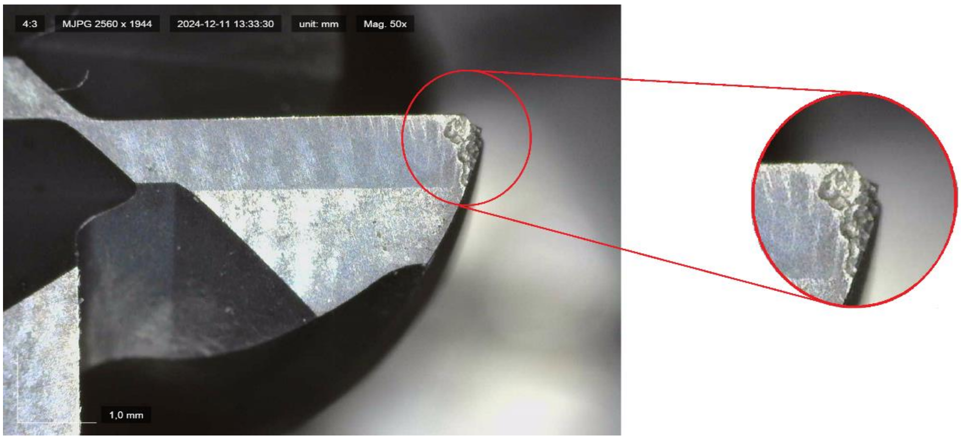
$$CEF_{tool} = \frac{CEF_{electric * K}}{3.6} * \frac{1000}{W_{tool}} \quad (12)$$

In the scope of this experiment, T_{tool} is implemented by measuring the average flank wear with a microscopic measurement device for each cutting tool and then predicting the approximate time for each tool to reach the determined flank wear of 0.3mm. The measurement images of each cutting tool are shown in Figure 3.11.

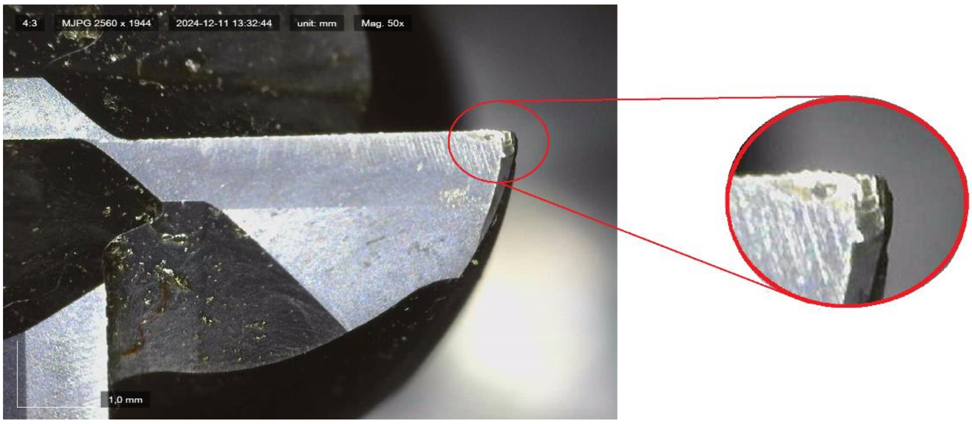
The resultant tool flank wear VB for CCF, dry, MQL-1, MQL-2, MQL-3 are measured as 0.89 mm, 1.13 mm, 0.27 mm, 0.19 mm and 0.21 mm respectively, with dry machining causing the highest wear and MQLs resulting with the lowest wear results as expected.



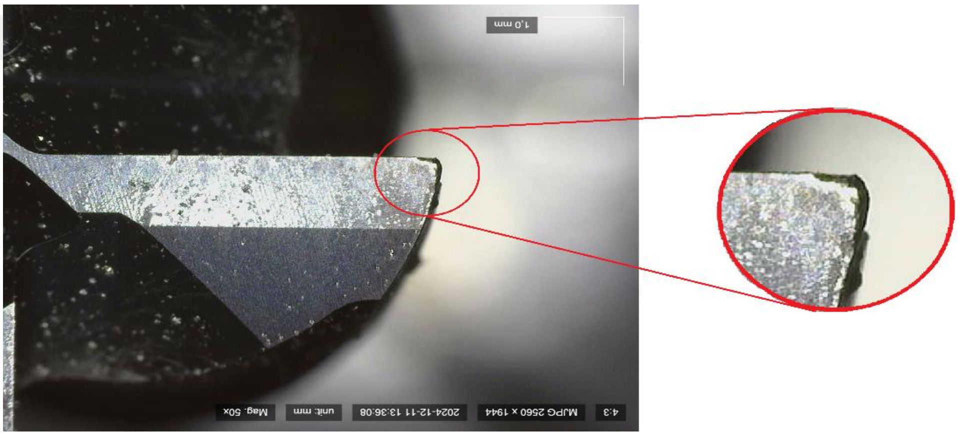
CCF



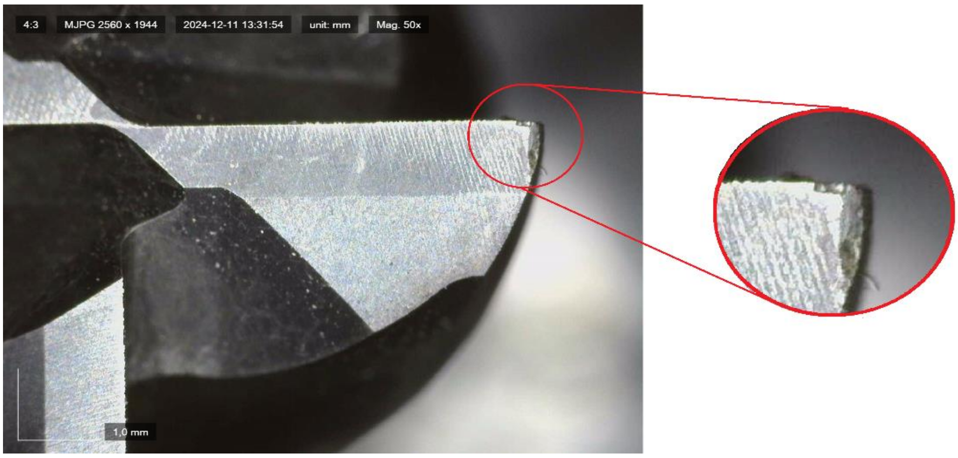
Dry



MQL-1



MQL-2



MQL-3

Figure 3.11 Flank wear on cutting tools

As illustrated in Figure 3.12 the relationship between flank wear and cutting time can generally be segmented into three distinct phases [131]. The initial phase, known as the break-in period, is characterized by a rapid rise in wear, which then transitions into a slower, more stable rate often resembling an exponential pattern. Following this is the steady-state wear phase, where wear progression becomes nearly linear relative to cutting time. Finally, the failure phase emerges, displaying varying wear patterns depending on the specific combinations of tool and workpiece materials being used.

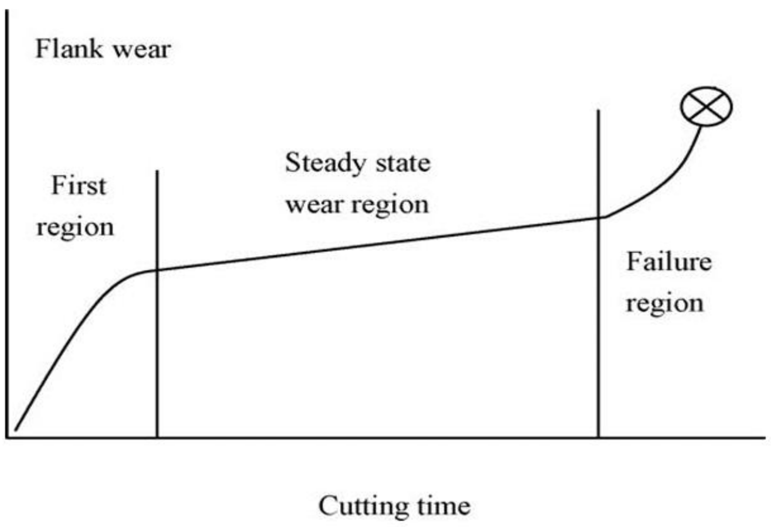


Figure 3.12 Typical curve of flank wear vs. cutting time [131]

In the studies that involve end milling of Inconel 718 using coated carbide inserts, it is difficult for the break-in period to be prominently observed in the flank wear with respect to cutting time. This implies that the phase is extremely brief, occurring early in the first cutting pass for each new insert, during which flank wear quickly surpasses to 0.3 mm [132]. While in the reality of the machining phenomena, several parameters such as increasing heat and possible work hardening changes the wear occurrence over time, it is not possible to measure the wear occurrence simultaneously without the accurate equipment. In the scope of this study, flank wear measurement is done after each cutting tool is completed three separate milling operations. By considering the total actual machining time and resultant average flank wear of each blade of the cutting tools, an approximate estimation of the tool life limit has been done. The adapted method resulted in CCF utilization showing an approximately 25% increase in the tool life when compared to dry machining. The average of MQL operations exceeded both with up to four times the tool life of CCF. The detailed results are shown in "Results and Discussion" section of the report.

3.6.1.4 Carbon Emissions of the Raw Material

Calculation of the carbon emissions of the material $CE_{material}$ as a result of a machining operation requires determination of two variables, CEF of the material ($CEF_{material}$) and the amount of material that is machined or simply the total mass of the chip removed (M_{chip}) as shown in Equation (13). IPCC defines $CEF_{material}$ as the amount of CO_2 produced by a unit of material per kg and determines this value with respect to the carbon intensity and embodied energy of the reference material [19]. This calculation, however, is rather difficult in cases of combination of multiple materials such as alloys. The $CEF_{material}$ value for Inconel 718 is selected as 17.5 kgCO2/kg in this study with respect to the study done by Cica and Kramar [124].

$$CE_{material} = CEF_{material} * M_{chip} \tag{13}$$

Quantification of M_{chip} can be done in two alternative ways. In the first method, the mass of the workpiece can be measured before and after the machining operation and the difference between these values can be taken as M_{chip}. In the other alternative, M_{chip} can be calculated by considering the density of the material ($d_{Inconel718}$) and material removal rate (MRR) per machining time (t_{cut}). For milling operations MRR is a value that is dependent on the parameters of feed rate (F), width of cut (W) and depth of cut (D) respectively as shown in Equation (14). In this study, machining conditions are feed rate of 318 mm / min, width of cut of 10 mm and depth of cut of 1 mm. Total measured cutting time is 36 seconds and density of the material is 8.19 gr / cm^3. Naturally, since this experiment adapts constant values for each of these parameters in every cutting condition, the resultant emissions for this section will be equal for all cutting conditions.

$$MRR = F * W * D / 1000 \tag{14}$$

$$M_{chip} = MRR * \frac{t_{cut} * \text{dInconel718}}{60} \quad (15)$$

3.6.1.5 Carbon Emissions of the Chip

The formed chips as the result of machining processes require an additional recycling process usually by being collected in an electrical furnace. The emissions resulting from the energy required to sustain this process are also considered as a part of the overall carbon footprint of the machining operation. Recycling of chips is commonly employed for material recovery, but the electricity consumption and associated carbon emissions vary based on material type of the scrap being processed. Different recovery technologies and criteria apply to each material, leading to variations in energy demand. Consequently, the calculation of carbon emission factor of chip (CEF_{chip}) is based on its standard coal equivalent. This study adapted the value of 3.7 kgCO2/kg for CEF_{chip} with respect to the study done by Cica and Kramar [124]. The calculation of CE_{chip} is shown in Equation (16) and similarly to $CE_{material}$, the resultant emission is equal for all cutting conditions.

$$CE_{chip} = CEF_{chip} * M_{chip} \quad (16)$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Cutting Force

The resultant cutting force results can be seen in Figure 4.1. Upon examining the cutting force values, it is observed that the highest cutting forces are from dry, followed by CCF, MQL applications using TMPTOE oil (MQL-1), PE oil with a VI of 180 (MQL-3), and PE oil with a VI of 221 (MQL-2), in descending order. The results indicate that all MQL oils consistently provides lower cutting forces than CCF and dry. On average, the cutting forces of MQL operations resulted as being 19.51% lower than the cutting forces of the dry operations and 6.96% lower than the CCF. One of the notable features of MQL is its ability to achieve improved lubrication effects in the cutting zone compared to CCF due to better penetration with aerosol sprayed at high pressure between the cutting tool and workpiece. This enhanced lubrication effect reduces friction, facilitating chip removal, and consequently leads to a decrease in cutting forces [133]. Moreover, an internal analysis of polymeric esters reveals that an increase in viscosity index correlates with decreased cutting forces. A higher viscosity index indicates lower sensitivity of viscosity to temperature changes in the oil, which is crucial for maintaining consistent machining. Particularly in processes involving materials with low thermal conductivity, like Inconel 718 material in this study, a high viscosity index has a positive effect due to the high temperature variations in the cutting zone resulting from heat accumulation.

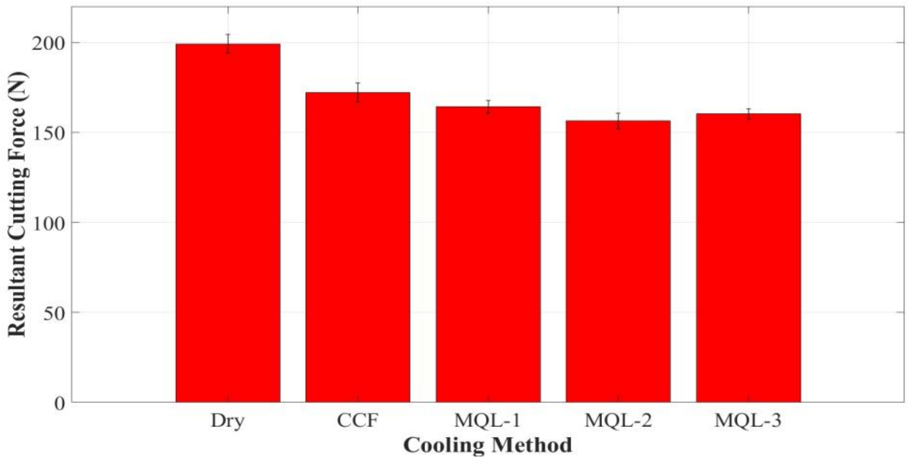


Figure 4.1 Resultant cutting force results

4.2 Surface Roughness

The results of surface quality align with the cutting force outcomes. When comparing areal surface roughness values, it is observed that, regardless of the oil used, all MQL applications yield lower surface roughness values compared to dry and CCF as shown in Figure 4.2. While dry environment and CCF showed average areal surface roughness of 1.854 µm and 1.730 µm respectively, MQL-1, MQL-2 and MQL-3 resulted with 1.689 µm, 1.438 µm and 1.687 µm. The average of the MQL operations resulted as 7.24% lower than the CCF. The difference is further increased when compared to dry machining with the MQL average being 13.48% lower. When the MQL oils are examined individually, it is noted that polymeric ester-based oils result in lower surface roughness values. Due to the low thermal conductivity of Inconel 718, the heat accumulated in the cutting zone cannot be effectively dissipated, adversely affecting the cutting tool and leading to surface degeneration. The mist effect generated by MQL application in the cutting zone, coupled with its exceptional penetration capability, plays a crucial role in reducing the accumulated heat in the environment [133]. Furthermore, the ester-based base oils used in MQL applications, known for their high thermal and chemical stability, enable stable cooling and lubrication throughout the cutting process, contributing to a reduction in surface roughness values.

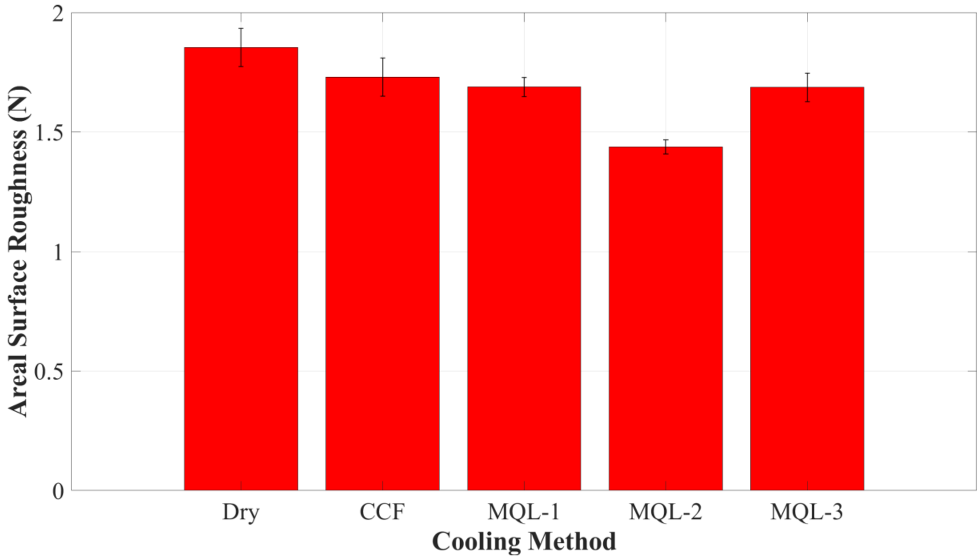


Figure 4.2 Areal surface roughness results

4.3 Surface Topography

Surface topography is one of the most important outcomes related to the surface integrity of machined parts. In Figure 4.3, the surface topographies of the slot bottom surfaces obtained after the experiments can be seen. It is observed that the surface topography values are in line with the areal surface roughness values. The desired outcome of surface topography measurement is a low peak-to-valley ratio which is obtained when the surfaces are relatively even and when the occurrence of surface dimples are few. These surface irregularities suggest a rougher, less consistent texture, which can negatively impact the performance of components in various applications. Uneven and coarse surfaces tend to increase friction and wear. It leads to more contact points and increases uneven stress distribution. The highest peak-to-valley values, non-uniform surface structures, and distinct tool marks are observed under dry conditions, whereas a relatively better surface was obtained with CCF compared to dry. However, on all surfaces where MQL was used, significantly lower peak-to-valley values, fewer tool traces, and more homogeneous and uniform surfaces were achieved compared to both dry and CCF. This can be explained by the good lubrication and cooling properties provided by MQL due to its high penetration capability. When the MQL oils are evaluated among themselves, it is observed that the polymeric ester-based MQL oils (MQL-2 and MQL-3) yielded better results than TMPTO (MQL-1), with the best results obtained from MQL-2, which is a polymeric ester-based MQL oil with a high viscosity index. This result may be caused by its enhanced lubrication film stability and superior thermal resistance. The higher viscosity index allows the lubricant to maintain its consistency across a wider temperature range, ensuring continuous and effective lubrication at the tool–workpiece interface. This reduces friction, minimizes tool wear, and leads to smoother surface finishes with fewer defects.

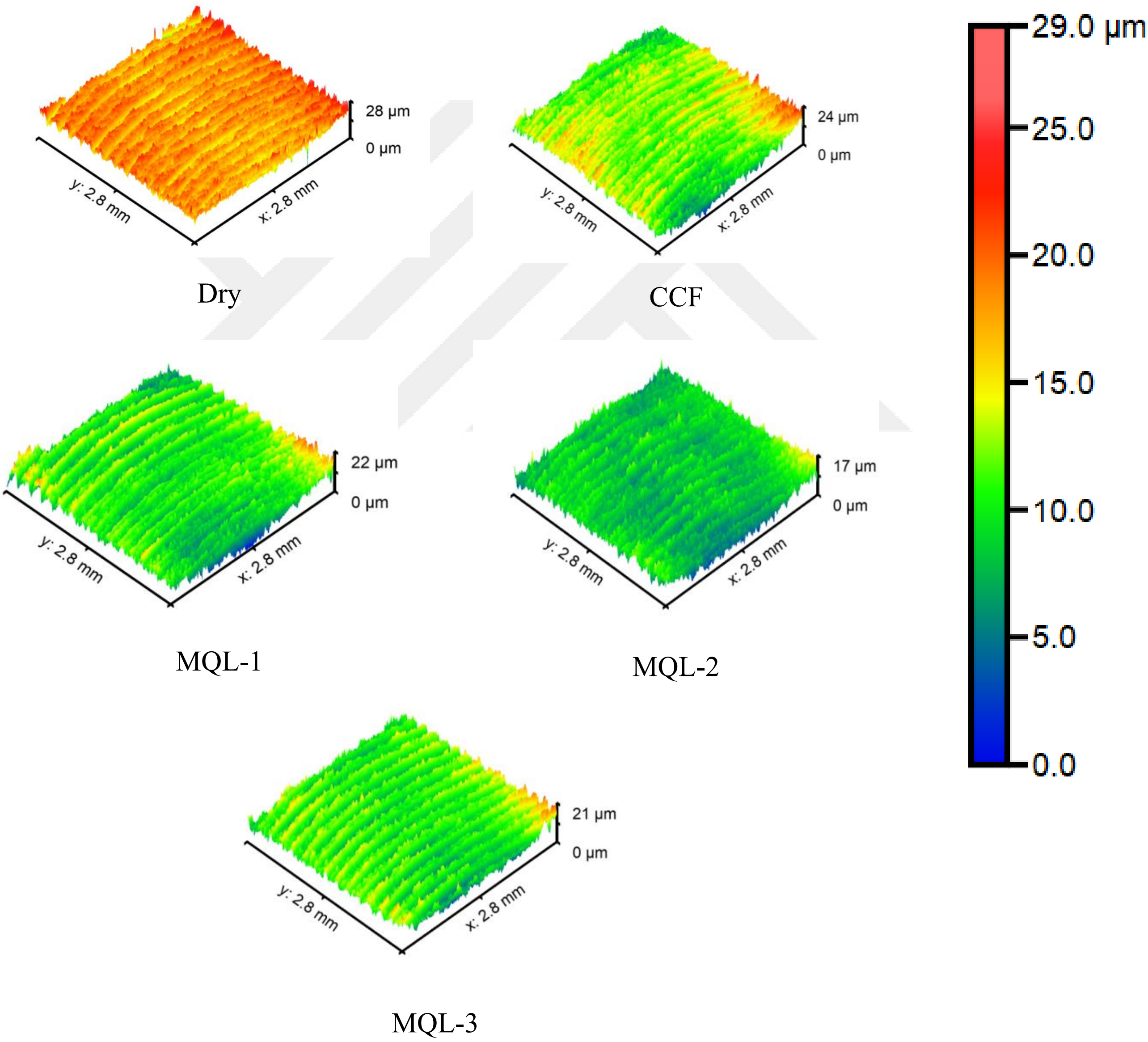


Figure 4.3 Surface topography images

4.4 Carbon Emissions

4.4.1 Resultant Carbon Emissions from Electricity

The calculated results of energy consumption and regarding carbon emissions of each experiment are given in Table 4.1. The factors that contribute to the consumption of electricity during a machining operation only include energy spent during the cutting stage as shown in Equation (3). The calculations for obtaining energy spent during cutting stage (E_{cut}) requires adapting Equations (1), (4) and (5)(5). The F_R values of Equation (1) is obtained with the utilization of dynamometer. Afterwards, with respect to Equation (5) P_{cut} and with respect to Equation (4) E_{cut} is obtained for each experiment as given in Table 4.1. Since the cutting stage energy consumption is only dependent on the cutting forces, resultant emission ratios are the same as cutting forces. The visual representation is shown in Figure 4.4.

Table 4.1 Carbon emissions due to electric consumption

Unit	N	N	N	N	N	m / min	kW	kW	kWh	kg CO_2 / kwh	kg CO_2
Parameter	F_y	F_x	F_y	F_R	Mean F_R	V_{cut}	P_{cut}	E_{cut}	Total E_{cut}	CEF_{elec}	$CE_{electric}$
Experiment											
Dry_1	137	84	62	172.25			0.1435	0.000478			
Dry_2	154	107	87	206.72	199.11		0.1723	0.000574	0.001659		0.000902
Dry_3	157	115	99	218.35			0.1820	0.000607			
CCF_1	128	76	60	160.50			0.1337	0.000446			
CCF_2	138	85	65	174.63	172.25		0.1455	0.000485	0.001435		0.000780
CCF_3	141	89	72	181.62			0.1514	0.000505			
MQL_1_1	122	64	62	151.08			0.126	0.00042			
MQL_1_2	126	76	61	159.29	164.19	50	0.133	0.000442	0.001368	0.5434	0.000743
MQL_1_3	148	87	61	182.19			0.152	0.000506			
MQL_2_1	104	51	60	130.45			0.109	0.000362			
MQL_2_2	116	60	83	154.74	156.36		0.129	0.00043	0.001303		0.000708
MQL_2_3	135	81	95	183.88			0.153	0.000511			
MQL_3_1	110	52	85	148.42			0.124	0.000412			
MQL_3_2	117	60	88	158.22	160.26		0.132	0.000439	0.001336		0.000726
MQL_3_3	135	66	88	174.14			0.145	0.000484			

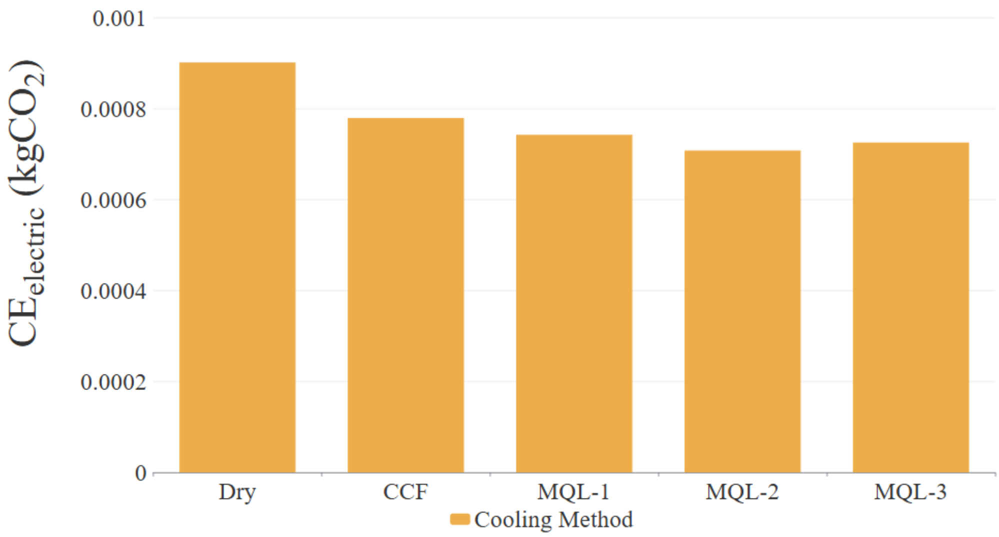


Figure 4.4 Resultant $CE_{electric}$ values

4.4.2 Resultant Carbon Emissions from Coolant-Lubricant Oil

The calculation of $CE_{coolant}$ covers both the emissions due to production and disposal of the oils as it is stated in Equation (6). However, the disposing stage is only included in the utilization of CCF since the other alternatives' coolant usage are either nonexistent or minimal, therefore negligible. Carbon emissions of oil production are related to the emission factor and the total amount of the oil as stated in Equation (7). The amount of oil is a variable that dependent on flow rate and application time as shown in Equation (9) and the CEF_{oil} is calculated with respect to Equation (10). Density values of the oils are obtained from their manufacturers. The resultant emissions are shown in Table 4.2. CCF emissions resulted as 1932 times average of MQL emissions. Due to having the same amount of usage and close density values, the emissions of MQL resulted very close to each other.

Table 4.2 Total emission of coolant-lubricants

Unit	s	g/cm^3	L	kg CO_2/L		kg CO_2	kg CO_2/L	kg CO_2	kg CO_2
Parameter	t	d	CC	CEF_{oil}	δ	CE_{oil}	CEF_{wc}	CE_{wc}	$CE_{c/l}$
Experiment									
Dry		0							
CCF		1.03	0.79167	3.194	0.08	0.06743	0.2	0.659	4.50781
MQL 1		0.9407	0.00079	2.917	1.00	0.00231	0	0	0.00231
MQL 2		0.9632	0.00079	2.987	1.00	0.00236	0	0	0.00236
MQL 3	57	0.9505	0.00079	2.948	1.00	0.00233	0	0	0.00233

4.4.3 Resultant Carbon Emissions of the Cutting Tool

T_{tool} values of each cutting tool are calculated by considering the wear occurrence is constant for each experiment. During the calculation of CEF_{tool}, in Equation (12) original W_{tool} value of 9.5 gr from the study of Rajemi et al. [130] is taken with respect to Li's [19] calculation method. Following Li's calculation method in Equation (11), this experiments W_{tool} is adapted. The resultant cutting tool emissions are shown in Table 4.3. Compared to dry and CCF, MQL on average decreased CE_{tool} by 81.2% and 74.9% respectively. Between the MQL oils, MQL-2 performed the best in terms of tool flank wear and therefore resulted as the one with the least amount of CE_{tool}. It resulted 9.4% lower than the MQL-3 and 29.6% lower than MQL-1. Their respective graph is shown in Figure 4.5.

Table 4.3 Emissions from cutting tool production

Unit	s	s	kg CO_2/kg	kg	kg CO_2
Parameter	t_{cut}	T_{tool}	CEF_{tool}	W_{tool}	CE_{tool}
Experiment					
Dry		9.07			6.5935
CCF		12.13			4.9301
MQL-1	36	40	23.833	0.0697	1.4951
MQL-2		56.82			1.0525
MQL-3		51.45			1.1623

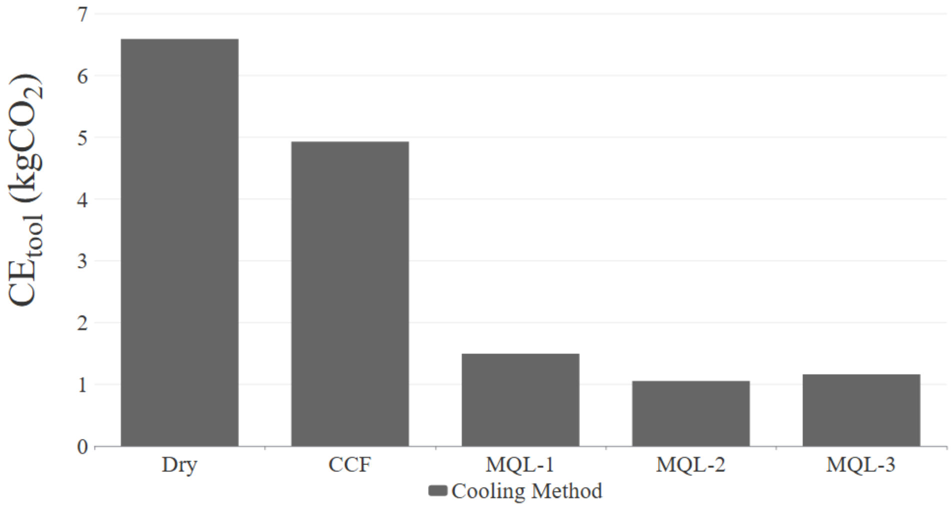


Figure 4.5 Resultant CE_{tool} values

4.4.4 Resultant Carbon Emissions of the Raw Material

Since the machining conditions were the same for each experiment the total removed material was equal in all the experiments. The resultant carbon emissions from the production of the amount of removed material is calculated with respect to Equation (13). MRR which is a required variable for calculation of M_{chip} is a function of feed, width and depth of cut in the milling operations and is calculated by using Equation (14). By also considering the cutting time and density of the material M_{chip} is obtained with Equation (15). The calculation for $CE_{material}$ resulted as:

From Equation (14):

MRR = F * W * D / 1000

= 318 * 10 * 1 / 1000

= 3.18 cm^3 / min

From Equation (15):

M_{chip} = MRR * $d_{Inconel718}$ * t_{cut} / 60

= 3.18 * 8.19 * 36 / 60

= 15.626 gr = 0.01563 kg

From Equation (13):

$CE_{material} = CEF_{material} * M_{chip}$

= 17.5 * 0.01563

= 0.273 kg CO_2

4.4.5 Resultant Carbon Emissions of the Chip

Lastly, the amount of released carbon emissions as the result of the recycling of the chips of Inconel 718 is calculated with respect to Equation (16), resulted as:

From Equation (16):

$CE_{chip} = CEF_{chip} * M_{chip}$

= 3.7 * 0.01563

= 0.0578 kg CO_2

4.4.6 Resultant Total Carbon Emissions

The summation of all the emissions considered for different cooling-machining methods is depicted in Table 4.4 .Since the common values of CE_{chip} and $CE_{material}$ are independent from the cooling conditions, they are excluded from the analysis of the results. Results indicate that, CE_{tool} is the prominent factor with the most emissions indifferent from the experiment type. The following factor which results with most emissions is $CE_{c/l}$ for each experiment other than dry machining. While the $CE_{electric}$ values have resulted with the least impact, it is important to be reminded that the electricity spent during the standby / idle stages of the experiment was not included and therefore the outcome may differ from the actuality. The total carbon emissions of each cooling method are visually depicted in Figure 4.6.

Table 4.4 The carbon emissions of different cooling-machining methods

	Total Carbon Emissions (kg CO_2)					
Experiment	$CE_{electric}$	$CE_{c/l}$	CE_{tool}	$CE_{material}$	CE_{chip}	$\mathbf{CE_{Total}}$
Dry	0.000902	0	6.5935	0.273	0.0578	**6.925**
CCF	0.000780	4.50781	4.9301	0.273	0.0578	**9.769**
MQL-1	0.000743	0.00231	1.4951	0.273	0.0578	**1.829**
MQL-2	0.000708	0.00236	1.0525	0.273	0.0578	**1.386**
MQL-3	0.000726	0.00233	1.1623	0.273	0.0578	**1.496**

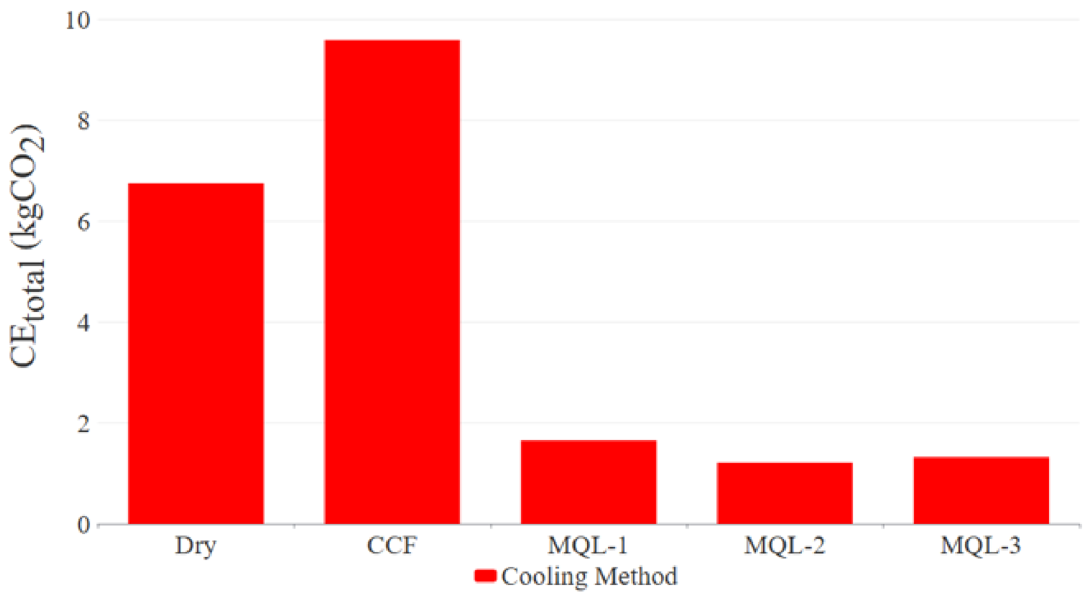


Figure 4.6 The carbon emissions of different cooling-machining methods

CHAPTER 5

CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

This study investigated MQL application as an alternative, more sustainable, and high-performance cooling/lubrication application in the slot milling operation of the difficult-to-cut Inconel 718 material, replacing traditional cutting fluid applications. Additionally, the study explored three different MQL oils, including one Trimethylolpropane Trioleate Type Polyol Ester and two Polymeric Esters, aiming to understand the impact of different oils on performance parameters. Furthermore, considering the increase of interest and importance of global warming, this study investigated additional performance of the different cooling strategies in terms of resultant carbon emissions in the name of sustainability with the aim of witnessing the impact of MQL compared to traditional alternatives. The results obtained can be summarized as follows:

- MQL application, irrespective of the oil type, led to reduced resultant cutting forces and areal slot bottom surface roughness compared to dry environment and CCF,
- Among the tested MQL oils, polymeric esters outperformed TMPTO ester in both cutting force reduction and surface quality improvement.
- Within the polymeric ester MQL oil group, those with a high viscosity index exhibited the best performance, attributed to their thermal stability during the cutting process.
- Surfaces produced using MQL demonstrated a more homogenous and uniform topography, characterized by smaller height fluctuations and lower peak-to-valley measurements than those obtained through dry or CCF.
- Microscopic measurements of tool wear revealed, MQL significantly reduced the wear occurrence compared to CCF and dry alternatives and therefore, improved the tool life.

- Sustainability assessment in terms of carbon footprint resulted with MQL alternatives causing the least amount of carbon emissions. Even though dry machining benefitted from not using coolant-lubricants and therefore resulting no emissions in that specific category, when the totality of the experiment is considered, its impact is overpassed by the emissions of cutting tool. The cutting tool utilized during the experiment having relatively high mass, further increased its percentage in the total emissions.

5.2 Recommendations for Future Works

For future research in the field of sustainability in terms of carbon emissions and MQL utilization in machining, the following recommendations can be given:

- The field of MQL has a promising future for the sustainable machining area. With several different modifications to the original, the alternatives such as Electrostatic MQL, Cryogenic MQL, Nanofluid MQL and Hybrid Nanofluid MQL are open for further investigation. This study can be expanded by considering the addition of these alternatives, also by alternating and applying multiple machining parameters.
- There are multiple beneficial methods such as ultrasonic assist that are adapted in machining with the aim of improving machining performance and several studies that took subject of comparing singular usage and combination of ultrasonic assist and MQL [90]. Carbon emission calculations of such experiments could be a useful addition for future studies.
- This study investigated the sustainability of milling of Inconel 718, which is a critical material for multiple industries but for mainly aerospace. However, there are many materials that are open for further research for the sake of sustainability, from the aerospace point of view, other commonly utilized materials such as Ti–6Al–4V, Hastelloy or Waspaloy can be taken for consideration, other machining processes also can be studied.

- Economics is also a prominent factor in sustainability. The cost of applying the cutting operation with respect to time, amount of resources used etc. can determine the sustainability of the operation and therefore can be considered for inclusion in such studies.
- While the calculation methods for emissions are based on the existing literature and it is safe to compare alternatives, it is difficult to be certain of their match with the reality of the operations. Since each CNC machine and MQL system have their own defining assets and specifications, utilization of additional measurement equipment such as power testing devices may help with more accurate measurement of electricity consumption.
- Generally, the flank wear of cutting tools increases parabolically as the result of work hardening phenomena and increasing temperatures in the cutting zone. While there are studies that adapted theoretical calculation methods for the tool life [122], it is difficult to formulate the reaction of tool to the utilized cutting fluids. Since the experiments in this study had relatively short amounts of cutting time, wear increase was assumed as linear. This can be improved by periodically measuring the flank wear of the tool until it reaches its end of life. This is more crucial for machining operations that require more time.

REFERENCES

[1] A. E. B. Hernández, T. Beno, and C. Fredriksson, "Energy and Cost Estimation of a Feature-based Machining Operation on HRSA". *Procedia CIRP*, vol. 61pp. 511–516, Jan. 2017.

[2] A. Thakur and S. Gangopadhyay, "State-of-the-art in surface integrity in machining of nickel-based super alloys". *International Journal of Machine Tools and Manufacture*, vol. 100pp. 25–54, Jan. 2016.

[3] A. De Bartolomeis, S. T. Newman, I. S. Jawahir, D. Biermann, and A. Shokrani, "Future research directions in the machining of Inconel 718". *Journal of Materials Processing Technology*, vol. 297p. 117260, Nov. 2021.

[4] T. Childs, K. Maekawa, T. Obikawa, and Y. Yamane, *Metal machining: Theory and applications*. 2000.

[5] C. Bruni, A. Forcellese, F. Gabrielli, and M. Simoncini, "Effect of the lubrication-cooling technique, insert technology and machine bed material on the workpart surface finish and tool wear in finish turning of AISI 420B". *International Journal of Machine Tools and Manufacture*, vol. 46(12–13), pp. 1547–1554, Oct. 2006.

[6] Y. J. Lee and H.-S. Yoon, "Modeling of cutting tool life with power consumption using Taylor's equation". *Journal of Mechanical Science and Technology*, vol. 37(6), pp. 3077–3085, Jun. 2023.

[7] A. Singh, S. Ghosh, and S. Aravindan, "State of art for sustainable machining of nickel-based alloys using coated and uncoated tools and machining of high strength materials using surface modified cutting tools". *Tribology International*, vol. 170p. 107517, Jun. 2022.

[8] A. Mehta *et al.*, "Influence of sustainable cutting environments on cutting forces, surface roughness and tool wear in turning of Inconel 718". *Materials Today: Proceedings*, vol. 5(2), pp. 6746–6754, 2018.

[9] J. Zhou, V. Bushlya, P. Avdovic, and J. E. Ståhl, "Study of surface quality in high speed turning of Inconel 718 with uncoated and coated CBN tools". *The International Journal of Advanced Manufacturing Technology*, vol. 58(1–4), pp. 141–151, Jan. 2012.

[10] M. Rahman, W. K. H. Seah, and T. T. Teo, "The machinability of inconel 718". *Journal of Materials Processing Technology*, vol. 63(1–3), pp. 199–204, Jan. 1997.

[11] H. Z. Li, H. Zeng, and X. Q. Chen, "An experimental study of tool wear and cutting force variation in the end milling of Inconel 718 with coated carbide inserts". *Journal of Materials Processing Technology*, vol. 180(1–3), pp. 296–304, Dec. 2006.

[12] L. Equeter, F. Ducobu, and P. Dehombreux, "Cutting Tools Replacement: Toward a Holistic Framework". *IFAC-PapersOnLine*, vol. 53(3), pp. 227–232, 2020.

[13] E. A. Rahim, A. A. Rahim, M. R. Ibrahim, and Z. Mohid, "Experimental Investigation of Supercritical Carbon Dioxide (SCCO2) Performance as a Sustainable Cooling Technique". *Procedia CIRP*, vol. 40pp. 637–641, 2016.

[14] S. Polo, E. M. Rubio, M. M. Marín, and J. M. Sáenz de Pipaón, "Evolution and Latest Trends in Cooling and Lubrication Techniques for Sustainable Machining: A Systematic Review". *Processes*, vol. 13(2), p. 422, Feb. 2025.

[15] T. He *et al.*, "Progress and trend of minimum quantity lubrication (MQL): A comprehensive review". *Journal of Cleaner Production*, vol. 386p. 135809, Feb. 2023.

[16] S. Debnath, M. M. Reddy, and Q. S. Yi, "Environmental friendly cutting fluids and cooling techniques in machining: a review". *Journal of Cleaner Production*, vol. 83pp. 33–47, Nov. 2014.

[17] A. K. Sharma, A. K. Tiwari, and A. R. Dixit, "Effects of Minimum Quantity Lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: A comprehensive review". *Journal of Cleaner Production*, vol. 127pp. 1–18, Jul. 2016.

[18] B. Purvis, Y. Mao, and D. Robinson, "Three pillars of sustainability: in search of conceptual origins". *Sustainability Science*, vol. 14(3), pp. 681–695, May 2019.

[19] C. Li, Y. Tang, L. Cui, and P. Li, "A quantitative approach to analyze carbon emissions of CNC-based machining systems". *Journal of Intelligent Manufacturing*, vol. 26(5), pp. 911–922, Oct. 2015.

[20] G. Navaneethan *et al.*, "A review of automated cutting tool selection methods". *The International Journal of Advanced Manufacturing Technology*, vol. 133(3–4), pp. 1063–1082, Jul. 2024.

[21] P. Pranav, E. Sneha, and S. Rani, "Vegetable oil-based cutting fluids and its behavioral characteristics in machining processes: a review". *Industrial Lubrication and Tribology*, vol. 73(9), pp. 1159–1175, Dec. 2021.

[22] S. Qun and Z. Weimin, "Carbon Footprint Analysis in Metal Cutting Process", in *Proceedings of the 1st International Conference on Mechanical Engineering and Material Science*, Paris, France: Atlantis Press, 2012.

[23] Intergovernmental Panel on Climate Change (IPCC), "Annex VII: Glossary", in *Climate Change 2021 – The Physical Science Basis*, Cambridge University Press, pp. 2215–2256, 2023.

[24] H. Zheng and K. Liu, "Machinability of Engineering Materials", in *Handbook of Manufacturing Engineering and Technology*, London: Springer London, pp. 1–34, 2013.

[25] T. M. Smith *et al.*, "Phase transformation strengthening of high-temperature superalloys". *Nature Communications*, vol. 7(1), p. 13434, Nov. 2016.

[26] G. R. Thellaputta, P. S. Chandra, and C. S. P. Rao, "Machinability of Nickel Based Superalloys: A Review". *Materials Today: Proceedings*, vol. 4(2), pp. 3712–3721, Jan. 2017.

[27] E. O. Ezugwu, Z. M. Wang, and A. R. Machado, "The machinability of nickel-based alloys: a review". *Journal of Materials Processing Technology*, vol. 86(1–3), pp. 1–16, Feb. 1999.

[28] H. Qi, M. Azer, and A. Ritter, "Studies of standard heat treatment effects on microstructure and mechanical properties of laser net shape manufactured INCONEL 718". *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*, vol. 40(10), pp. 2410–2422, 2009.

[29] D. Zhu, X. Zhang, and H. Ding, "Tool wear characteristics in machining of nickel-based superalloys". *International Journal of Machine Tools and Manufacture*, vol. 64pp. 60–77, Jan. 2013.

[30] "INSG Insight Nickel-Based Super Alloys" April 2013 – no.20 https://insg.org/wp-content/uploads/2019/01/INSG_Insight_20_Nickel_Alloys_2013.pdf

[31] D. Dudzinski, A. Devillez, A. Moufki, D. Larrouquère, V. Zerrouki, and J. Vigneau, "A review of developments towards dry and high speed machining of Inconel 718 alloy". *International Journal of Machine Tools and Manufacture*, vol. 44(4), pp. 439–456, Mar. 2004.

[32] D. M. D’Addona, S. J. Raykar, and M. M. Narke, "High Speed Machining of Inconel 718: Tool Wear and Surface Roughness Analysis". *Procedia CIRP*, vol. 62pp. 269–274, 2017.

[33] A. De Bartolomeis, S. T. Newman, D. Biermann, and A. Shokrani, "State-of-The-Art Cooling and Lubrication for Machining Inconel 718". *Journal of Manufacturing Science and Engineering*, vol. 143(5), May 2021.

[34] H. A. Kishawy and A. Hosseini, "Environmentally Conscious Machining", pp. 205–238, 2019.

[35] J. Haider and M. S. J. Hashmi, "Health and Environmental Impacts in Metal Machining Processes", in *Comprehensive Materials Processing*, Elsevier, pp. 7–33, 2014.

[36] F. W. Taylor, "On the Art of Cutting Metals". *Transactions of the American Society of Mechanical Engineers*, vol. 28pp. 31–279, Jan. 1906.

[37] P. J. Liew, A. Shaaroni, N. A. C. Sidik, and J. Yan, "An overview of current status of cutting fluids and cooling techniques of turning hard steel". *International Journal of Heat and Mass Transfer*, vol. 114pp. 380–394, Nov. 2017.

[38] P. S. Sheng and S. Oberwalleney, "Life-Cycle Planning of Cutting Fluids—A Review". *Journal of Manufacturing Science and Engineering*, vol. 119(4B), pp. 791–800, Nov. 1997.

[39] S. C. Veldhuis, G. Fox-Rabinovich, and L. S. Shuster, "Coolants and lubricants in metal cutting", in *Handbook of Lubrication and Tribology: Volume I Application and Maintenance, Second Edition*, pp. 11–12, 2006.

[40] E. Brinksmeier, D. Meyer, A. G. Huesmann-Cordes, and C. Herrmann, "Metalworking fluids—Mechanisms and performance". *CIRP Annals*, vol. 64(2), pp. 605–628, Jan. 2015.

[41] J. Singh, S. S. Gill, M. Dogra, and R. Singh, "A review on cutting fluids used in machining processes". *Engineering Research Express*, vol. 3(1), p. 012002, Mar. 2021.

[42] G. Singh, V. Aggarwal, and S. Singh, "Critical review on ecological, economical and technological aspects of minimum quantity lubrication towards sustainable machining". *Journal of Cleaner Production*, vol. 271p. 122185, Oct. 2020.

[43] H. Cohen and E. M. White, "Metalworking Fluid Mist Occupational Exposure Limits: A Discussion of Alternative Methods". *Journal of Occupational and Environmental Hygiene*, vol. 3(9), pp. 501–507, Sep. 2006.

[44] E. O. Bennett, "Water based cutting fluids and human health". *Tribology International*, vol. 16(3), pp. 133–136, Jun. 1983.

[45] N. King, L. Keranen, K. Gunter, and J. Sutherland, "Wet Versus Dry Turning: A Comparison of Machining Costs, Product Quality, and Aerosol Formation", Mar. 2001.

[46] F. Pusavec, D. Kramar, P. Krajnik, and J. Kopac, "Transitioning to sustainable production – part II: evaluation of sustainable machining technologies". *Journal of Cleaner Production*, vol. 18(12), pp. 1211–1221, Aug. 2010.

[47] A. Shokrani, V. Dhokia, and S. T. Newman, "Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids". *International Journal of Machine Tools and Manufacture*, vol. 57pp. 83–101, Jun. 2012.

[48] S. Pawanr and K. Gupta, "Dry Machining Techniques for Sustainability in Metal Cutting: A Review". *Processes*, vol. 12(2), p. 417, Feb. 2024.

[49] R. Yigit, E. Celik, F. Findik, and S. Koksal, "Effect of cutting speed on the performance of coated and uncoated cutting tools in turning nodular cast iron". *Journal of Materials Processing Technology*, vol. 204(1–3), pp. 80–88, Aug. 2008.

[50] P. Sivaiah, D. Chakradhar, and R. G. Narayanan, "Sustainable manufacturing strategies in machining", in *Sustainable Manufacturing Processes*, Elsevier, pp. 113–154, 2023.

[51] Y. Yildiz and M. Nalbant, "A review of cryogenic cooling in machining processes". *International Journal of Machine Tools and Manufacture*, vol. 48(9), pp. 947–964, Jul. 2008.

[52] B. Zohuri, "The Beginning and Concept of Cryogenics, Basic Principles", in *Physics of Cryogenics*, Elsevier, pp. 387–473, 2018.

[53] S. Ravi and P. Gurusamy, "Role of cryogenic machining: A sustainable manufacturing process". *Materials Today: Proceedings*, vol. 37(Part 2), pp. 316–320, Jan. 2021.

[54] N. Khanna *et al.*, "Review on design and development of cryogenic machining setups for heat resistant alloys and composites". *Journal of Manufacturing Processes*, vol. 68pp. 398–422, Aug. 2021.

[55] V. P. Astakhov, "Ecological Machining: Near-dry Machining", in *Machining*, London: Springer London, pp. 195–223, 2008.

[56] H. Tschätsch and A. Reichelt, "Cutting fluids (coolants and lubricants)", in *Applied Machining Technology*, Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 349–352, 2009.

[57] Chetan, S. Ghosh, and P. Venkateswara Rao, "Application of sustainable techniques in metal cutting for enhanced machinability: a review". *Journal of Cleaner Production*, vol. 100pp. 17–34, Aug. 2015.

[58] R. H. Namlu, B. Lotfi, and S. E. Kılıç, "Enhancing machining efficiency of Ti-6Al-4V through multi-axial ultrasonic vibration-assisted machining and hybrid nanofluid minimum quantity lubrication". *Journal of Manufacturing Processes*, vol. 119pp. 348–371, Jun. 2024.

[59] M. N. Sharif, S. Pervaiz, and I. Deiab, "Potential of alternative lubrication strategies for metal cutting processes: a review". *The International Journal of Advanced Manufacturing Technology*, vol. 89(5–8), pp. 2447–2479, Mar. 2017.

[60] B. Boswell, M. N. Islam, I. J. Davies, Y. R. Ginting, and A. K. Ong, "A review identifying the effectiveness of minimum quantity lubrication (MQL) during conventional machining". *The International Journal of Advanced Manufacturing Technology*, vol. 92(1–4), pp. 321–340, Sep. 2017.

[61] G. B. Moretti *et al.*, "Sustainable machining practices: a comparative study of MQL and MQL with wheel cleaning jet applied to different abrasives". *The International Journal of Advanced Manufacturing Technology*, vol. 132(5–6), pp. 2395–2409, May 2024.

[62] J. C. Lopes *et al.*, "Manufacturing process linked to the MQL compared to flood lubrication applied to the grinding of VP50IM steel using black silicon carbide wheel".

The International Journal of Advanced Manufacturing Technology, vol. 120(5–6), pp. 4179–4190, May 2022.

[63] Y. Dubey *et al.*, "A Review on Green Machining: Environmental and Economic Impacts of Cutting Fluids". *E3S Web of Conferences*, vol. 505p. 01030, Mar. 2024.

[64] P. Nagendramma and S. Kaul, "Development of ecofriendly/biodegradable lubricants: An overview". *Renewable and Sustainable Energy Reviews*, vol. 16(1), pp. 764–774, Jan. 2012.

[65] B. Kamyab, R. Beims, D. W. Chambers, A. S. Bassi, and C. Xu, "Sustainable production of high-performance bio-based hydraulic fluids from vegetable oils: Recent advances, current challenges, and future perspectives". *Biomass and Bioenergy*, vol. 183p. 107160, Apr. 2024.

[66] J. H. Schmidt, "Life cycle assessment of five vegetable oils". *Journal of Cleaner Production*, vol. 87pp. 130–138, Jan. 2015.

[67] C. Hu *et al.*, "Ester Oils Prepared from Fully Renewable Resources and Their Lubricant Base Oil Properties". *ACS Omega*, vol. 6(25), pp. 16343–16355, Jun. 2021.

[68] T. Tawakoli, M. J. Hadad, and M. H. Sadeghi, "Investigation on minimum quantity lubricant-MQL grinding of 100Cr6 hardened steel using different abrasive and coolant–lubricant types". *International Journal of Machine Tools and Manufacture*, vol. 50(8), pp. 698–708, Aug. 2010.

[69] M. Hadad and B. Sadeghi, "Thermal analysis of minimum quantity lubrication-MQL grinding process". *International Journal of Machine Tools and Manufacture*, vol. 63pp. 1–15, Dec. 2012.

[70] Y. Zhang, C. Li, D. Jia, D. Zhang, and X. Zhang, "Experimental evaluation of the lubrication performance of MoS2/CNT nanofluid for minimal quantity lubrication in Ni-based alloy grinding". *International Journal of Machine Tools and Manufacture*, vol. 99pp. 19–33, Dec. 2015.

[71] R. K. Gunda and S. K. R. Narala, "Electrostatic high-velocity solid lubricant machining system for performance improvement of turning Ti–6Al–4V alloy". *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 233(1), pp. 118–131, Jan. 2019.

[72] A. de Bartolomeis, S. T. Newman, and A. Shokrani, "High-speed milling Inconel 718 using Electrostatic Minimum Quantity Lubrication (EMQL)". *Procedia CIRP*, vol. 101pp. 354–357, Jan. 2021.

[73] A. G. Bailey, "Electrostatic phenomena during powder handling". *Powder Technology*, vol. 37(1), pp. 71–85, Jan. 1984.

[74] V. Sivalingam *et al.*, "A mathematical approach of evaluating sustainability indicators in milling of aluminium hybrid composite by different eco-friendly cooling strategies". *Sustainable Materials and Technologies*, vol. 36p. e00605, Jul. 2023.

[75] A. Gupta, R. Kumar, H. Kumar, and H. Garg, "Sustainable Machining Using Hybrid Nanofluids Under Minimum Quantity Lubrication (MQL)", *Heliyon*, vol. 10pp. 573–584, 2019.

[76] M. K. Gupta *et al.*, "Experimental characterisation of the performance of hybrid cryo-lubrication assisted turning of Ti–6Al–4V alloy". *Tribology International*, vol. 153p. 106582, Jan. 2021.

[77] M. Iruj, S. Yaqoob, J. A. Ghani, H. Jaber, N. Saibani, and M. Alkhedher, "State-of-the-art hybrid lubrication (Cryo-MQL) supply systems, performance evaluation, and optimization studies in various machining processes". *Results in Engineering*, vol. 22p. 102090, Jun. 2024.

[78] R. Mallick, R. Kumar, A. Panda, and A. K. Sahoo, "Current Status of Hard Turning in Manufacturing: Aspects of Cooling Strategy and Sustainability". *Lubricants*, vol. 11(3), p. 108, Feb. 2023.

[79] L. Zou, Y. Huang, M. Zhou, and Y. Yang, "Effect of cryogenic minimum quantity lubrication on machinability of diamond tool in ultraprecision turning of 3Cr2NiMo steel". *Materials and Manufacturing Processes*, vol. 33(9), pp. 943–949, Jul. 2018.

[80] A. C. Okafor and P. M. Jasra, "Effects of milling methods and cooling strategies on tool wear, chip morphology and surface roughness in high speed end-milling of Inconel-718". *International Journal of Machining and Machinability of Materials*, vol. 21(1/2), p. 3, 2019.

[81] L. Sterle, P. Krajnik, and F. Pušavec, "The effects of liquid-CO2 cooling, MQL and cutting parameters on drilling performance". *CIRP Annals*, vol. 70(1), pp. 79–82, 2021.

[82] M. Jamil, N. He, M. K. Gupta, W. Zhao, and A. M. Khan, "Tool wear mechanisms and its influence on machining tribology of face milled titanium alloy under sustainable hybrid lubri-cooling". *Tribology International*, vol. 170p. 107497, Jun. 2022.

[83] F. S. F. Ribeiro *et al.*, "New knowledge about grinding using MQL simultaneous to cooled air and MQL combined to wheel cleaning jet technique". *The International Journal of Advanced Manufacturing Technology*, vol. 109(3–4), pp. 905–917, Jul. 2020.

[84] S. Chinchanikar, S. S. Kore, and P. Hujare, "A review on nanofluids in minimum quantity lubrication machining". *Journal of Manufacturing Processes*, vol. 68pp. 56–70, Aug. 2021.

[85] M. A. Makhesana, K. M. Patel, G. M. Krolczyk, M. Danish, A. K. Singla, and N. Khanna, "Influence of MoS2 and graphite-reinforced nanofluid-MQL on surface roughness, tool wear, cutting temperature and microhardness in machining of Inconel 625". *CIRP Journal of Manufacturing Science and Technology*, vol. 41pp. 225–238, Apr. 2023.

[86] M. Hemmat Esfe, M. Bahiraei, and A. Mir, "Application of conventional and hybrid nanofluids in different machining processes: A critical review". *Advances in Colloid and Interface Science*, vol. 282p. 102199, Aug. 2020.

[87] L. Syam Sundar, M. K. Singh, and A. C. M. Sousa, "Investigation of thermal conductivity and viscosity of Fe3O4 nanofluid for heat transfer applications". *International Communications in Heat and Mass Transfer*, vol. 44pp. 7–14, May 2013.

[88] A. A. Junankar, J. K. Purohit, and N. V. Bhende, "Effective utilization of nanofluids for machining process enhancement". *AIP Conference Proceeding*, vol. 2148p. 030040, Sep. 2019.

[89] J. Sarkar, P. Ghosh, and A. Adil, "A review on hybrid nanofluids: Recent research, development and applications". *Renewable and Sustainable Energy Reviews*, vol. 43pp. 164–177, Mar. 2015.

[90] R. H. Namlu, B. Lotfi, and S. E. Kiliç, "Multi-axial ultrasonic vibration-assisted machining of Inconel 718 using Al2O3-CuO hybrid nanofluid MQL". *Procedia CIRP*, vol. 123pp. 89–94, Jan. 2024.

[91] B. Lotfi, R. H. Namlu, and S. E. Kılıç, "Machining performance and sustainability analysis of Al_2O_3-CuO hybrid nanofluid MQL application for milling of Ti-6Al-4V". *Machining Science and Technology*, vol. 28(1), pp. 29–73, Jan. 2024.

[92] Y. Kamata and T. Obikawa, "High speed MQL finish-turning of Inconel 718 with different coated tools". *Journal of Materials Processing Technology*, vol. 192–193pp. 281–286, Oct. 2007.

[93] P. Sivaiah, V. Ajay Kumar G, M. Singh M, and H. Kumar, "Effect of novel hybrid texture tool on turning process performance in MQL machining of Inconel 718 superalloy". *Materials and Manufacturing Processes*, vol. 35(1), pp. 61–71, Jan. 2020.

[94] M. Q. Saleem and A. Mehmood, "Eco-friendly precision turning of superalloy Inconel 718 using MQL based vegetable oils: Tool wear and surface integrity evaluation". *Journal of Manufacturing Processes*, vol. 73pp. 112–127, Jan. 2022.

[95] S. Zhang, J. F. Li, and Y. W. Wang, "Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions". *Journal of Cleaner Production*, vol. 32pp. 81–87, Sep. 2012.

[96] N. Khanna, J. Airao, G. Kshitij, C. K. Nirala, and H. Hegab, "Sustainability analysis of new hybrid cooling/lubrication strategies during machining Ti6Al4V and Inconel 718 alloys". *Sustainable Materials and Technologies*, vol. 36p. e00606, Jul. 2023.

[97] N. H. Abdul Halim, C. H. Che Haron, and J. Abdul Ghani, "Sustainable Machining of Hardened Inconel 718: A Comparative Study". *International Journal of Precision Engineering and Manufacturing*, vol. 21(7), pp. 1375–1387, Jul. 2020.

[98] Y. Kaynak, "Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining". *The International Journal of Advanced Manufacturing Technology*, vol. 72(5–8), pp. 919–933, May 2014.

[99] V. Tebaldo, G. G. di Confiengo, and M. G. Faga, "Sustainability in machining: "Eco-friendly" turning of Inconel 718. Surface characterisation and economic analysis". *Journal of Cleaner Production*, vol. 140pp. 1567–1577, Jan. 2017.

[100] M. Danish, M. K. Gupta, S. Rubaiee, A. Ahmed, M. Sarıkaya, and G. M. Krolczyk, "Environmental, technological and economical aspects of cryogenic assisted hard machining operation of inconel 718: A step towards green manufacturing". *Journal of Cleaner Production*, vol. 337p. 130483, Feb. 2022.

[101] S. Zhang, J. F. Li, and Y. W. Wang, "Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions". *Journal of Cleaner Production*, vol. 32pp. 81–87, Sep. 2012.

[102] "Iscar EC-A4 100-22C10-72 Cutting Tool Specifications", Internet: https://webshop.iscar.com.br/catalogue/product/1933277 [04.07.2025].

[103] E. Budak and Y. Altintas¸, "Analytical Prediction of Chatter Stability in Milling—Part I: General Formulation". *Journal of Dynamic Systems, Measurement, and Control*, vol. 120(1), pp. 22–30, Mar. 1998.

[104] Y. Altintas, "MODELING APPROACHES AND SOFTWARE FOR PREDICTING THE PERFORMANCE OF MILLING OPERATIONS AT MAL-UBC". *Machining Science and Technology*, vol. 4(3), pp. 445–478, Nov. 2000.

[105] D. Nečas and P. Klapetek, "Gwyddion: an open-source software for SPM data analysis". *Open Physics*, vol. 10(1), pp. 181–188, Feb. 2012.

[106] "Dino-Lite AM4113T Optical Microscope", Internet: https://www.dino-lite.com/products_detail.php?index_id=95 [06.07.2025].

[107] "Tapping Torque Test", Internet: https://www.tapping-torque-test.com/en/ttt-system/ [06.07. 2025].

[108] J. Rigo and P. Feinle, "SRV Tribometer". *Encyclopedia of Lubricants and Lubrication*, Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 1949–1956, 2014.

[109] G. Gaurav, A. Sharma, G. S. Dangayach, and M. L. Meena, "Assessment of jojoba as a pure and nano-fluid base oil in minimum quantity lubrication (MQL) hard-turning of Ti–6Al–4V: A step towards sustainable machining". *Journal of Cleaner Production*, vol. 272p. 122553, Nov. 2020.

[110] H. H. Masjuki, M. A. Maleque, A. Kubo, and T. Nonaka, "Palm oil and mineral oil based lubricants—their tribological and emission performance". *Tribology International*, vol. 32(6), pp. 305–314, Jun. 1999.

[111] B. L. Tai, J. M. Dasch, and A. J. Shih, "EVALUATION AND COMPARISON OF LUBRICANT PROPERTIES IN MINIMUM QUANTITY LUBRICATION MACHINING". *Machining Science and Technology*, vol. 15(4), pp. 376–391, Oct. 2011.

[112] T. J. Bruno et al., "Thermophysical properties of polyol ester lubricants", NIST Interagency/Internal Report (NISTIR), National Institute of Standards and Technology, Gaithersburg, MD, Aug. 2019, Internet: https://doi.org/10.6028/NIST.IR.8263 [11.07.2025].

[113] M. Jamil, A. Iqbal, N. He, and Q. Cheok, "Thermophysical Properties and Heat Transfer Performance of Novel Dry-Ice-Based Sustainable Hybrid Lubri-Coolant". *Sustainability*, vol. 14(4), p. 2430, Feb. 2022.

[114] F. Pape et al., "Comprehensive Evaluation of the Rheological, Tribological, and Thermal Behavior of Cutting Oil and Water-Based Metalworking Fluids". *Lubricants*, vol. 13(5), p. 219, May 2025.

[115] B. Bhushan, "Surface roughness analysis and measurement techniques", *Mechanics & Materials Science*, pp. 49–119, 2000.

[116] B. Bhushan, *Modern Tribology Handbook, Two Volume Set*. CRC Press, 2000.

[117] Y. F. Yapan, K. Türkeli, U. Emiroğlu, E. Bahçe, and A. Uysal, "Machining and Sustainability Performance Comparison for the Milling Process of Al6082 Alloy Under Various Minimum Quantity Lubrication Conditions". *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 12(2), pp. 409–430, Mar. 2025.

[118] "Name Origin of Carbon", Internet: https://www.ciaaw.org/carbon.htm [04.07.2025].

[119] T. Gao, Q. Liu, and J. Wang, "A comparative study of carbon footprint and assessment standards". *International Journal of Low-Carbon Technologies*, vol. 9(3), pp. 237–243, Sep. 2014.

[120] "Greenhouse Gas Protocol IPCC Global Warming Potential Values", Internet: https://ghgprotocol.org/sites/default/files/2024-08/Global-Warming-PotentialValues%20%28August%202024%29.pdf [04.07.2025].

[121] J. B. Dahmus and T. G. Gutowski, "An Environmental Analysis of Machining", in *Manufacturing Engineering and Materials Handling Engineering*, ASMEDC, pp. 643–652, Jan. 2004.

[122] A. Uysal, J. R. Caudill, J. Schoop, and I. S. Jawahir, "Minimising carbon emissions and machining costs with improved human health in sustainable machining of austenitic stainless steel through multi-objective optimisation". *International Journal of Sustainable Manufacturing*, vol. 4(2/3/4), p. 281, 2020.

[123] A. K. Cakir, "A new approach to minimize carbon emission rate in turning processes". *International Journal of Low-Carbon Technologies*, vol. 16(4), pp. 1444–1452, Dec. 2021.

[124] D. Cica and D. Kramar, "Machinability investigation and sustainability analysis of high-pressure coolant assisted turning of the nickel-based superalloy Inconel 718". *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 237(1–2), pp. 43–54, Jan. 2023.

[125] D. Kordonowy, "A power assessment of machining tools", BSc, Massachusetts Institute of Technology, Dept. of Mechanical Engineering, 2002.

[126] R. Singh, J. S. Dureja, M. Dogra, M. Kumar Gupta, M. Jamil, and M. Mia, "Evaluating the sustainability pillars of energy and environment considering carbon emissions under machining ofTi-3Al-2.5 V". *Sustainable Energy Technologies and Assessments*, vol. 42p. 100806, Dec. 2020.

[127] H. Yang et al., "Life cycle climate performance evaluation of electric vehicle thermal management system under Chinese climate and driving condition". *Applied Thermal Engineering*, vol. 228p. 120460, Jun. 2023.

[128] E. Duman, Y. F. Yapan, H. Salvi, M. A. Sofuoğlu, N. Khanna, and A. Uysal, "Investigation of ultrasonic vibration assisted orthogonal turning under dry and minimum quantity lubrication conditions and performing sustainability analyses". *Journal of Cleaner Production*, vol. 434p. 140187, Jan. 2024.

[129] "ISO 8688-2:1989(en) Tool life testing in milling — Part 2: End milling", Internet: https://www.iso.org/obp/ui/#iso:std:iso:8688:-2:ed-1:v1:en [04.07.2025].

[130] M. F. Rajemi, P. T. Mativenga, and A. Aramcharoen, "Sustainable machining: selection of optimum turning conditions based on minimum energy considerations". *Journal of Cleaner Production*, vol. 18(10–11), pp. 1059–1065, Jul. 2010.

[131] A. Ber and S. Kaldor, "The First Seconds of Cutting, Wear Behaviour". *CIRP Annals*, vol. 31(1), pp. 13–17, Jan. 1982.

[132] H. Z. Li, H. Zeng, and X. Q. Chen, "An experimental study of tool wear and cutting force variation in the end milling of Inconel 718 with coated carbide inserts". *Journal of Materials Processing Technology*, vol. 180(1–3), pp. 296–304, Dec. 2006.

[133] R. H. Namlu, B. Çetin, B. Lotfi, and S. E. Kılıç, "Investigation of the Combined Effects of Ultrasonic Vibration-Assisted Machining and Minimum Quantity Lubrication on Al7075-T6". *Journal of Engineering*, vol. 2024(1), Jan. 2024.